COMMAND GUIDANCE SIMULATOR/TRAINER FOR SURFACE TO AIR MISSILE SYSTEMS

A Thesis Submitted
In partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By
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to the
DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

JANUARY, 1976

CERTIFICATE

Certified that this work 'COMMAND GUIDANCE SIMULATOR/TRAINER FOR SURFACE TO AIR MISSILES' by Purushottam Parshad Varma has been carried out under my supervision and that it has not been submitted elsewhere for a degree.

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ACKNOWLEDGEMENTS

With profound gratitude, I wish to acknowledge the valuable guidance and persistent encouragement given to me by my supervisor, Dr.R.N.Biswas, in my present endeavour. In fact, I find it difficult to express my true feelings when I ponder back on the long hours of discussions that we have had, in which with enviable patience; he helped in unfolding the various 'ifs', 'whys' and 'hows' of the problem.

My acknowledgements are due to Dr.B.D.Aggarwal for his valuable suggestion and help in the mechanical design of the Flight -Controller.

I am grateful to the staff of the Central Workshop, Departmental Workshop, Stores and the Laboratory staff for their excellent co-operation and help in the fabrication work.

I am also indebted to Shri R.Pandey for his good typing.

My acknowledgements shall be incomplete without a mention of my family, who have patiently suffered my long hours in the laboratory. I have no words for my wife, who has undergone silent sacrifices for my sake and has stood by me like a leading star, encouraging me all the time, while I struggled with the problem.

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LIST OF ABBREVIATIONS AND SYMBOLS

1. ABBREVIATIONS

The following abbreviations have been used in the text:-

- FC - Flight-Controller
- LOS - Line of Sight. (Unless specified, it refers to LOS with the target).
- TF - Transfer Function
- SRD - Synthetic Rate Damping
- OA - Operational Amplifier ($\mu A741$).

2. SYMBOLS IN RELATION TO SYSTEM

- t - Time of missile-flight in seconds after the instant of launch.
- T_1 - Instant of time at which a step guidance command is applied
- 'O' - Cross-over point of the missile with the LOS to the target after take off.
- t_o - Time in seconds taken by a missile to reach the cross-over point 'O'.

R_o - Slant range of the missile (from the Launcher) when it reaches the cross-over point 'O'.

d - Distance between the Director and the Launcher.

h' - Hypothetical relative height assigned to the Director for launch geometry computations, to compensate for gravity drop at the instant of initial take-off.

g - Acceleration due to gravity.

3. SYMBOLS IN RELATION TO MISSILE

(a) The following symbols refer to the kinematic variables due to guidance and may apply to either pitch plane or the yaw plane:-

v - Linear lateral velocity.

a - Lateral acceleration.

θ - Lateral angular position of the missile in the viewing-plane.

w - Lateral angular velocity of the missile in the viewing-plane.

w_f - Steady state angular velocity of the missile in the viewing-plane.

$\dot{w}$ - Lateral angular acceleration.

(b) The following symbols refer to the kinematic variables due to the Initial conditions and relative target motion in the viewing plane:-

v_x/w_x - Component of missile linear/angular velocity along x-axis.

v_{y1}/w_{y1} - Component of missile linear/angular velocity along y-axis due to Initial conditions alone.

v_{y2}/w_{y2} - Component of missile linear/angular velocity along y-axis due to relative target motion alone.

v_z - Component of missile linear velocity along LOS

θ_x - x-co-ordinate

θ_{y1} - y-co-ordinate due to Initial conditions alone.

θ_{y2} - y-co-ordinate due to relative target motion alone.

(c) The following symbols refer to the Kinetic variables:

F - Instantaneous forward thrust of the rocket-motor.

W - Instantaneous weight of the missile in flight.

a_F - Instantaneous forward acceleration of the missile.

$\vec{V}_M$ - Instantaneous velocity (vector) of the missile.

v_O - Coasting speed of the missile.

u - Average speed of the missile.

R - Slant range of the missile

4. SYMBOLS IN RELATION TO TARGET

R_T - Instantaneous slant range of the target from the Director,

R_{TO} - Initial slant range at the time of launching the missile.

R_G - Instantaneous ground range of the target from the Director.

R_{GO} - Initial ground range from the Director.

h_T - Target altitude above ground.

V_T - Target speed.

5. SYMBOLS IN RELATION TO LAUNCH GEOMETRY

B_s - Initial bearing of the LOS to the target with reference to the ground-equipment reference axis.

E_s - Initial elevation of the target with reference to the ground plane.

B_L - Bearing at which a missile is launched with reference to the Reference axis.

E_L - Elevation at which a missile is launched.

B_c - Correction angle added to B_s to obtain B_L.

E_c - Correction angle added to E_s to obtain E_L.

6. <u>SYMBOLS FOR LOGICAL VARIABLES USED IN SYSTEM DESIGN</u>

CPF - Control Pulse Fire

CPR - Control Pulse Reset

CPG - Control Pulse Guidance (Enable)

$\overline{\text{CPG}}$ - Functionally Logical NOT of CPG

SYNOPSIS
of
M.Tech thesis submitted by
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January, 1976

COMMAND GUIDANCE SIMULATOR/TRAINER FOR SURFACE TO AIR MISSILE SYSTEMS

The present study has been undertaken with an aim towards indigenous development of a suitable training -aid for the progressive simulated training of personnel (Missile-Pilots), who are responsible for guiding a missile in flight,

A broad-based study has been carried out for a particular class of air-defence weapon systems i.e. the Low Level Surface to Air Radio Command-guided systems, based on optical/radar acquisition and tracking of a target and visual

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guidance of the missile. The guidance and the control functions of such a system have been analysed; and mathematical models in general terms, applicable to any other similar system, have been deduced.

A critical review of the mathematical models along with other relevant considerations, pertaining to the requirements of simulated training, has led to the evolution of three feasible simulation models, corresponding to a three -tier concept of levels of training i.e. the basic, the advanced and the 'on job' field training of the missile-pilots. Each simulation model envisages a different display system appropriate to the level of training.

Accordingly, it is possible to develop either three different simulator units or a single universal type of simulator, incorporating all the three models with facility to select either of the training-modes in conjunction with the appropriate display device. Since such a system is considered feasible without incurring any significant additional complexity of the equipment and cost, and at the same time gaining the advantages of standardization and flexibility of utilization; the concept of universal type of model is mooted and recommended for further development and ultimate adoption into service.

A laboratory model of the Command Guidance Simulator, corresponding to the basic training version of the

suggested simulation model has been successfully designed and fabricated.

The simulator unit is an analogue device which computes the instantaneous angular co-ordinates of both the missile under guidance control and a synthetic target. The initial conditions of the target i.e. its speed and range in terms of expected engagement-time, its bearing and elevation are preset on the front panel controls; and the dynamic trajectory of the target during the encounter can be varied either by a programmed tape-input or by the Instructor through dynamic pitch and yaw controls. It is possible to simulate the effect of a manoeuvering target by a JITTER control. The display consists of a single beam oscilloscope, with its interface-unit (a multiplexer) incorporated in the simulator unit. The missile and the synthetic target are displayed on the scope as two (beam-switched) intensity-modulated spots. The screen is calibrated for the normal field of view of the missile-pilot.

Facility for performance evaluation of the trainees has been incorporated, both quantitatively by strip-chart recordings and qualitatively for routine training by lamp indications.

A significant achievement of the work carried out is the design and development of a Flight-controller. The

initial intention was to make a compatible device which could be used to test the designed guidance simulation blocks. However, the device so developed , can in fact be used as an important indigenous substitute for the imported Flight-controllers. The device, though designed on an entirely different principle (strain-gauges), is fully compatible functionally with an existing imported Flight-controller in service.

Considerations for standardization of components and circuits, easy maintenance, and low cost commensurate with the requirements of reliability,have been the guiding factors in the design and fabrication of the device For instance, only one particular type of IC chip (μA 741) has been used throughout the system. Similarly, only one type each of the other active devices like transistors, junction FETs and diodes has been standardized to keep the maintenance inventory low. Adequate test-points, facilities for in-circuit testing and repair of printed circuit cards have been incorporated to enable quick fault-diagnosis and easy maintenance. Particular attention has been given to the location and accessibility of vital components e.g. the trimpots. No relays have been used and where necessary, all solid state switching has been performed.

CHAPTER I

INTRODUCTION

Surface to Air guided weapon systems form a vital link in the air-defence organization of a country. A small beginning has been made in our country in this significant field of air-defence. However, there has been total dependence on other countries for the equipment, technical know-how and even training of personnel. With an aim towards an indigenous system, the present study has been undertaken for the peace-time progressive training of personnel handling the equipment.

1.1 MOTIVATION

A guided weapon system, with a human operator in the feed-back loop, involves a very close-knit and intense man-machine interaction. The Missile-Pilot, the person who controls and guides the missile in flight, is the king-pin of the entire system, and it is on his sharp reflexes, skill and experience that the accuracy and overall effectiveness of the system depends. As these systems are usually deployed for the air-defence of vulnerable areas or vital installations of national importance, any lack of skill on the part of the human operator shall only compromise the national security.

Thus, there is a need for continuous intensive training of the missile-pilots to keep their reflexes sharp and to improve their proficiency. Training with live missles and targets is cumbersome as well as expensive;and therefore, the need for simulated training with a training-aid becomes imperative.

1.2 OBJECTIVE AND SCOPE

The present study has been undertaken with an aim to design and develop a simulator-trainer for the peace-time progressive training of the missile-pilots for a particular type i.e. the Radio Command guidance systems for low-level surface-to-air missiles.

Such systems are essentially rudimentary type of guided weapons with limited capability and are used for tactical air-defence of vulnerable points/areas against approaching hostile aircraft only. A human operator constitutes the feed-back loop. A target is acquired and tracked either optically or with the help of a tracking radar. The missile pilot guides the missile along his line of sight to the target. (Details for a typical system of this type are given in Chapter II).

1.3 APPROACH

The problem has been tackled in two phases:-

(a) The theoretical study in general terms and paper-design of a simulator applicable to the entire

class of weapon systems under study.

(b) The hardware design and realization using the parameters of a particular existing weapon system of the class.

The third obvious and important phase of trials i.e. to assess the effectiveness and realism incorporated, as compared to a live missile firing; has been excluded from the purview of the present study, because of limitations of time and the other administrative problems of arranging trials. It is hoped that the Defence R and D organization shall take up this aspect in due course of time.

The study has been carried out in the following steps:

(a) Study of an existing system with particular reference to its guidance system.

(b) Analysis of the various blocks in the guidance system to get a better comprehension of the functional role, and its mathematical modelling by deduction of transfer-functions in general terms applicable to any other similar system.

(c) Critical study of the above analysis for simulation models, keeping requirements of progressive training in mind, and leading to deduction of a block simulator model.

(d) Design and realization of the hardware for the simulator model, using analogue techniques. For this, the typical parameters of an existing system have been used.

1.4 CHAPTER ORGANIZATION

A brief introductory description of a typical low-level surface to Air command-guided weapon system is given in the next Chapter. Chapter III deals with the analysis and mathematical modelling of the guidance system;, while the simulation considerations are discussed and a block simulator model is developed in Chapter IV. Chapter V is concerned with the hardware design and its implementation; and Chapter VI concludes with a summary of results achieved and a discussion on the scope for improvement and further work yet to be done.

CHAPTER II

BRIEF DESCRIPTION OF A TYPICAL LOW-LEVEL SURFACE TO AIR RADIO COMMAND GUIDED WEAPON SYSTEM

The aim of this chapter is to give a brief introduction of a typical radio-command-guided weapon system with particular reference to the guidance techniques used.

2.1 GENERAL CHARACTERISTICS AND LIMITATIONS

Such a weapon system is envisaged primarily for tactical air-defence of vulnerable points/areas against low-flying attacking aircraft. The system is most effective against directly approaching hostile aircraft and has inherent limitations against receding and crosser targets, because of low missile speed and limited lateral acceleration capability of the missiles used.

2.2 BROAD OUTLINE PRINCIPLE OF COMMAND GUIDANCE

For the particular type of system under study, a human operator, called Missile-Pilot, acquires a target visually through a binocular with/without the help of a tracking radar, continues tracking it till it is within the firing range; fires a missile and then tracks both the missile and the target. He senses the angular error between the target and the missile, and applies appropriate correction commands through a transducer called FLIGHT-

CONTROLLER(FC). The corrective electrical commands, after suitable processing, are transmitted to the missile using a VHF or UHF carrier. A servo-system in the missile causes the missile to change its course in response to the guidance commands. The missile-pilot perceives the relative change and continues to apply command signals, till he 'gathers'[φ] the missile in his line of sight (LOS) with the target. His endeavour thereafter is to apply guidance commands such as to keep the missile gathered till interception of the missile and the target takes place and the target gets destroyed. In the event of missing the target, the missile destroys itself after a specific preset time.

Figure 2.1 illustrates the principle of a command guided system with a human operator in the feed-back loop. Fig. 2.2 gives the relative position of FC button for missile guidance. Fig. 2.3 depicts the difference between the guidance commands given by a good trained missile-pilot and an inexperienced person.

2.3 <u>WEAPON SYSTEM-HARDWARE</u>

For detailed discussion of command guidance and its simulation problem, it is necessary to acquire a little

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φ The term GATHERING is used aften in the missile system jargon . It implies a state when the lines of sight to the target and the missile coincide.

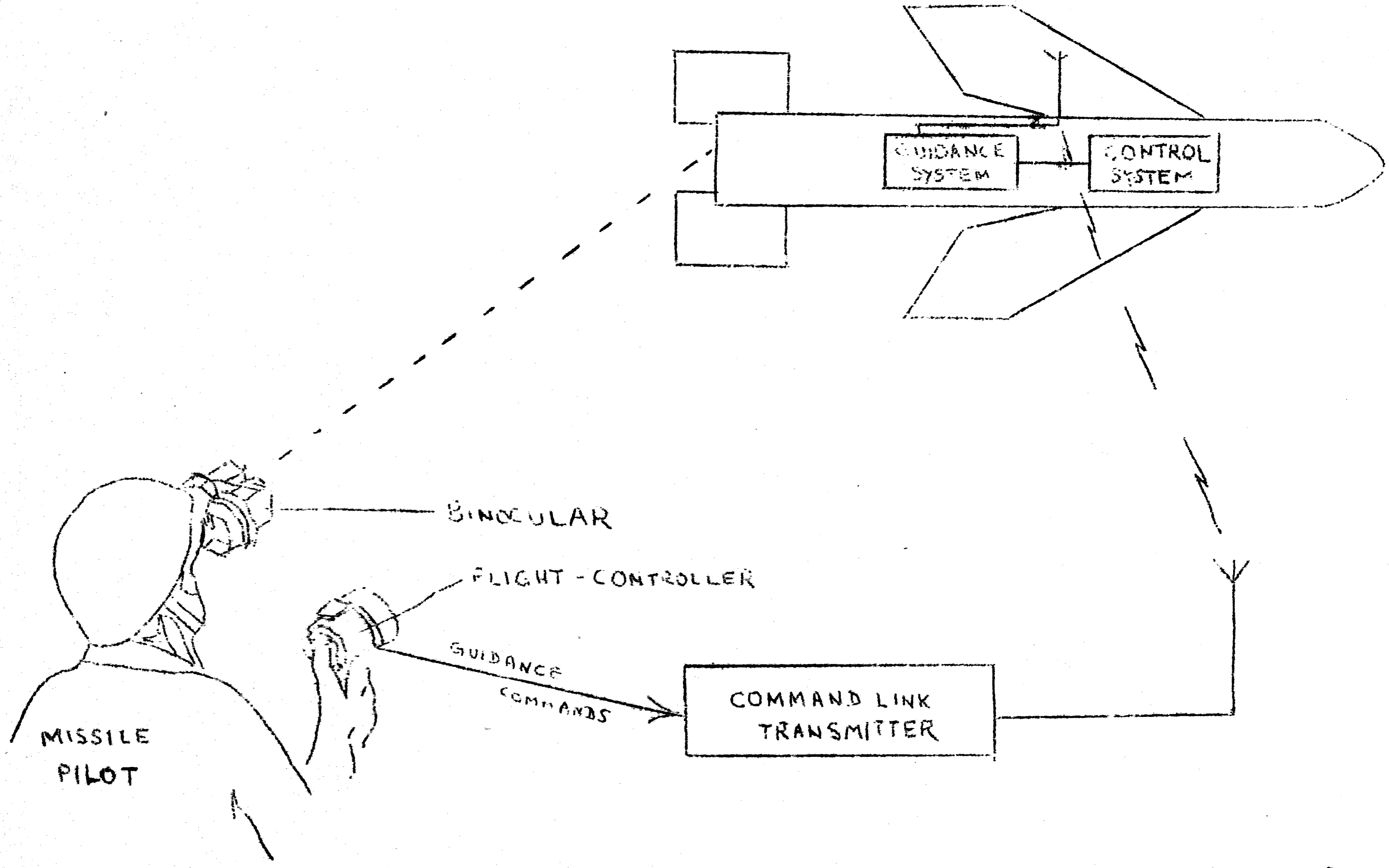


FIG. 2.1. PRINCIPLE OF COMMAND GUIDANCE

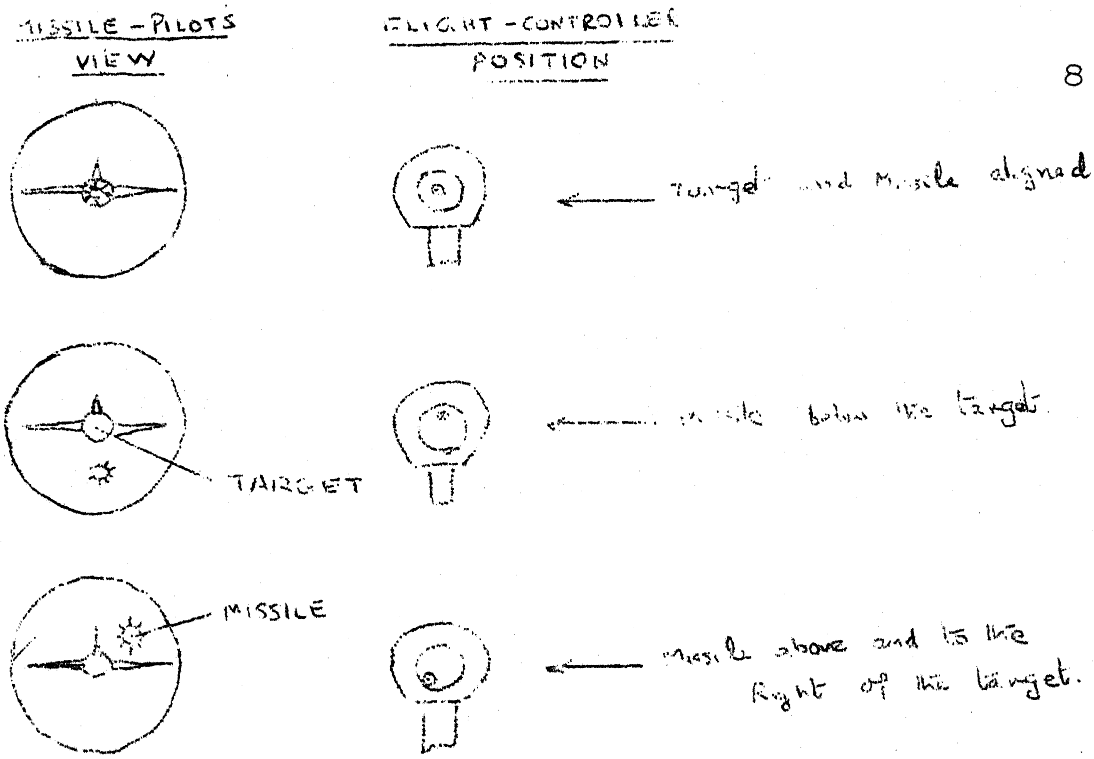


FIG. 2.2. ILLUSTRATION OF F.C. BUTTON POSITIONS FOR MISSILE GUIDANCE

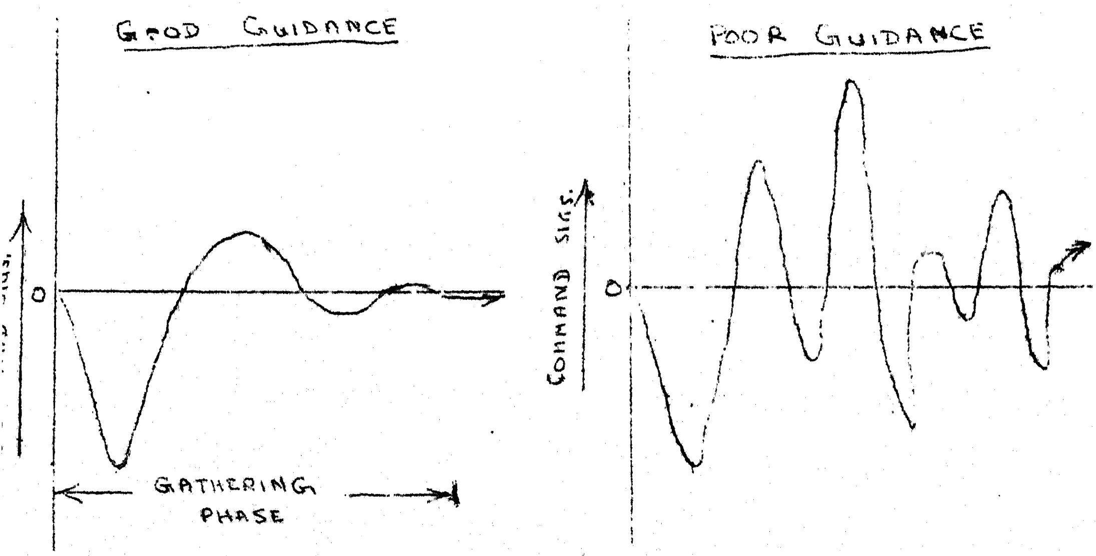


FIG. 2.3. ILLUSTRATION OF GOOD AND POOR GUIDANCE DEPENDING ON SKILL OF MISSILE-PILOT

preliminary knowledge of the essential and relevant hardware involved in the particular type of the weapon system.

The integrated weapon system consists of the ground equipment and the missile. Fig. 2.4 gives a typical layout of a guided missile fire-unit.

The ground equipment consists of :-

(a) Director - for overall control.

(b) Launcher- as the mobile launching pad for the missiles.

(c) Generator for the required power supplies.

(d) Signal communications equipment for communication among the crew and with others outside the Fire-unit.

(e) Transport vehicles

(f) Tracking radar (optional)

The functional roles of the Director and the Launcher and some of the relevant characteristics of the missile are described in the following sub-sections.

2.3.1 Director

The Director is a mobile master equipment and comprises of a number of units. The units relevant to missile guidance and control are:

a) Rotating structure for the missile pilot seat,

b) Command link transmitter,

and c) Launch geometry computer.

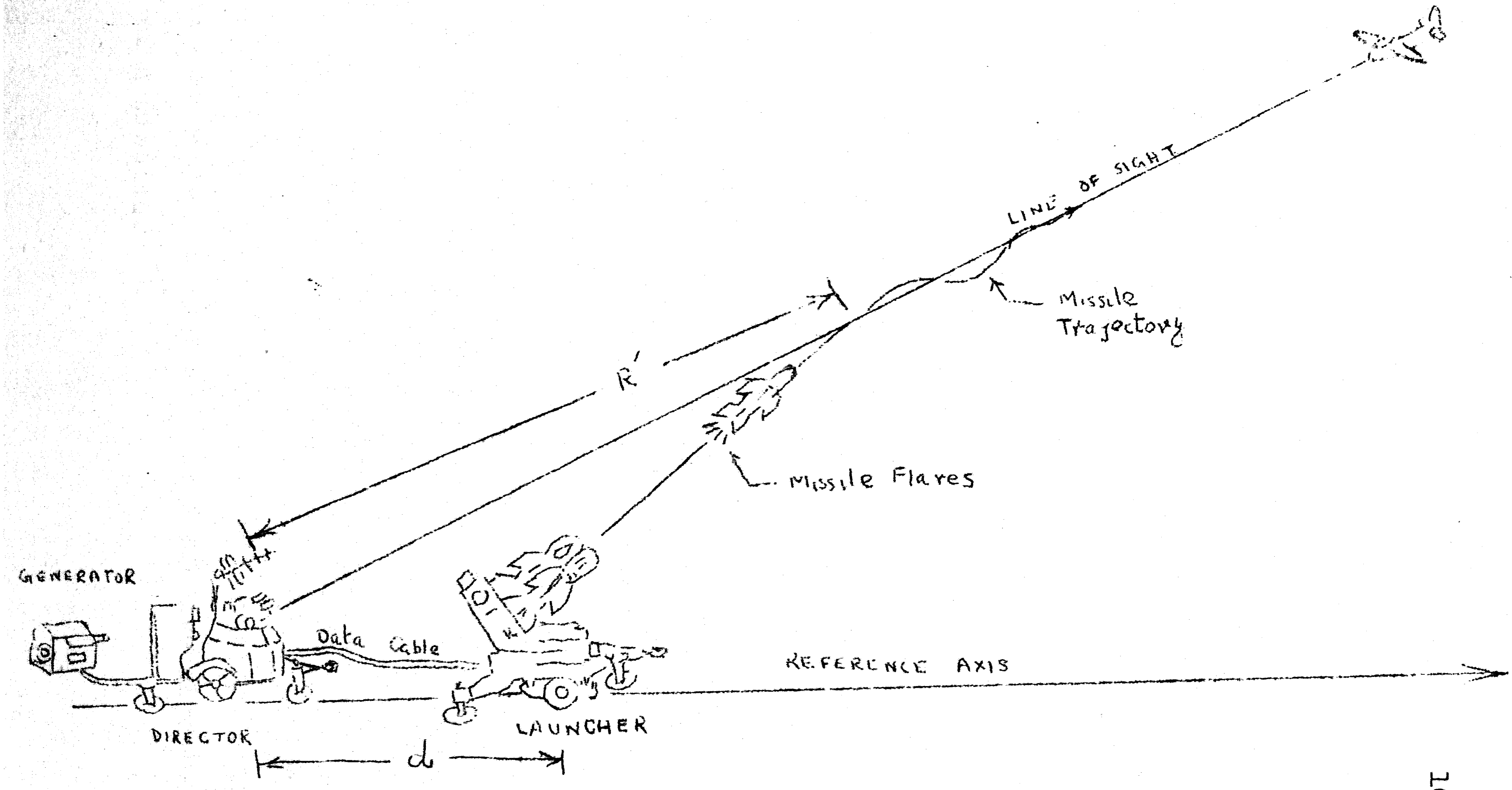


FIG. 2.4 TYPICAL LAYOUT OF A GUIDED MISSILE FIRE-UNIT

2.3.1.1 Rotating Structure

This can be rotated in azimuth by a servo-system, such that the missile-pilot seated on it faces the general direction of an approaching target. The missile-pilot sees through a binocular having a large magnification and a wide field of view. The binocular is mounted on a sight-arm, which the missile pilot holds with his hands.

The right hand side of the sight-arm carries a FLIGHT- CONTROLLER (FC). FC is a transducer for generating analogue electrical guidance commands independently in two planes i.e. the pitch and the yaw, in proportion to the displacement produced in a thumb-operated mechanical device having two degrees of freedom in the same plane. The nature of displacements applied to the FC by missile-pilot in relation to the error in the positions of the target and the missile have been illustrated in Fig. 2.2. The outputs of FC are bipolar DC voltages corresponding to the guidance commands in the pitch and the yaw planes. The positive polarity is usually assigned to UP/RIGHT commands and negative polarity to DOWN/LEFT commands.

The left hand side of the sight-arm carries a FIRING-TRIGGER, which when pressed by the missile pilot, triggers the electrically initiated-explosive circuits for the firing of a missile.

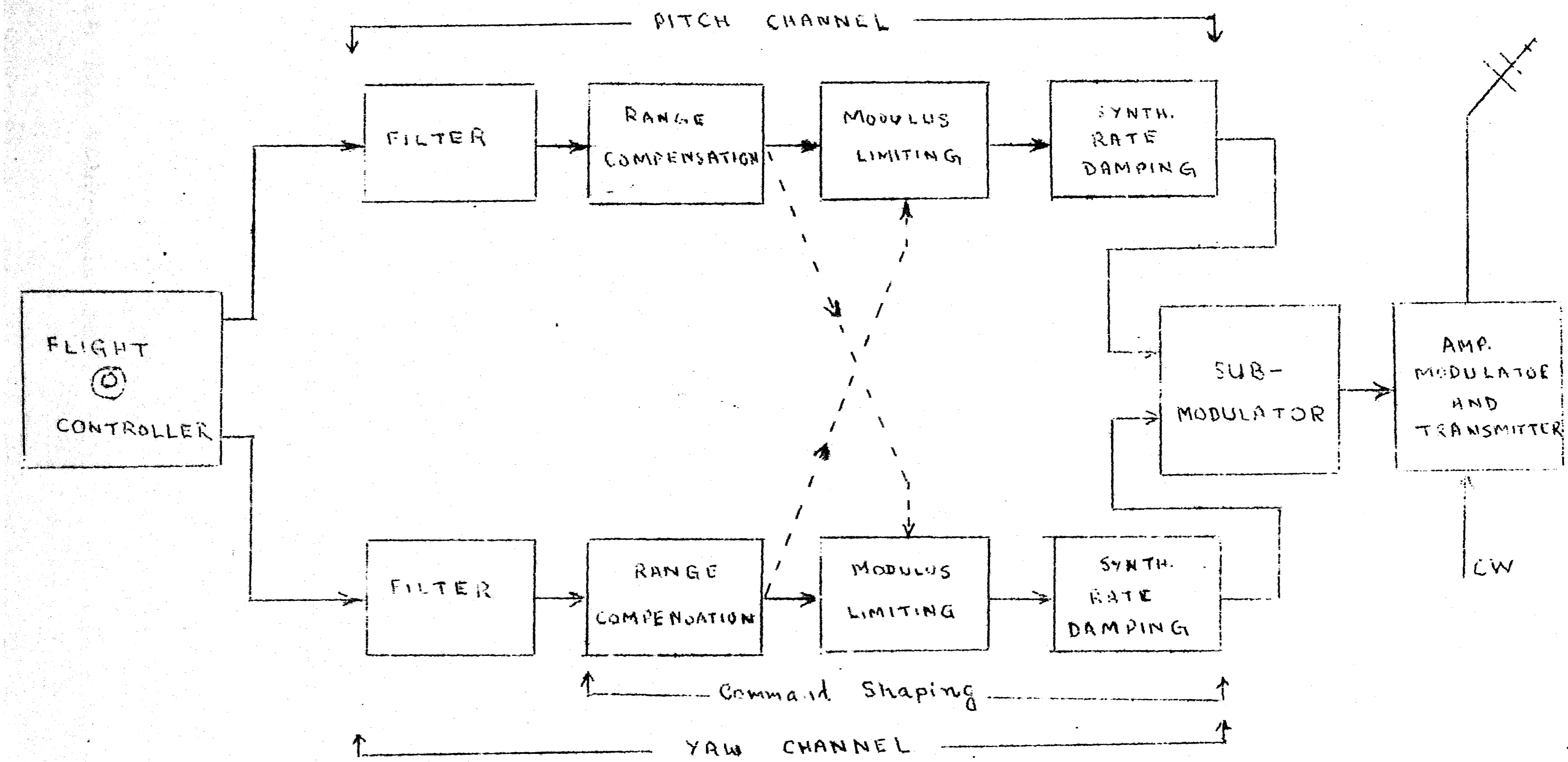


FIG. 2.5 BLOCK DIAGRAM - COMMAND LINK TRANSMITTER

the missile as range increases. Thus, the missile-pilot with range -compensation incorporated sees a constant missile response for a given FC demand.

(c) Modulus Limiting

This is required to ensure that the resultant total command with the simultaneous application of maximum demands in both pitch and yaw planes is not large enough to cause aerodynamic instability of the missile.

(d) Synthetic Rate Damping (SRD)

To avoid the effect of natural (weather-cock) frequency of the missile, the missile control system is required to incorporate lateral rate gyro damping. However, for reasons of economy; it is found convenient to shape the command signal such as to simulate the lateral rate damping in the ground equipment itself, by means of a notch-filter tuned to the weather-cock frequency of the missile.

(e) Sub-modulator

The shaped command signals are time-division-multiplexed in the form of a train of four distinct tone frequencies corresponding to the UP-DOWN and RIGHT-LEFT guidance demand in the pitch and yaw planes. The time interval for both the pitch and the yaw tone-pairs is fixed, but there is a differential dwell period for each tone within the tone-pair set.

For elucidation, if f_1, f_2, f_3, f_4 are the tone frequencies corresponding to the UP,DOWN,RIGHT and LEFT demands, then the gate-timing for tone-pairs f_1, f_2 for pitch plane and f_3, f_4 for yaw plane is same and remains constant. But, within each pair, the dwell period for f_1/f_3 and f_2/f_4 will be different depending upon the demand signal. For no demand condition, the dwell periods for all tone frequencies are equal.

(f) RF Modulator

The multiplexed tone-frequency train is then used for amplitude-modulating a CW and is transmitted to the missile through an antenna.

(g) Antenna

The antenna is mounted on the rotating-structure so that it always points towards the direction of the target and the missile. It has a characteristic of a wide beam lobe in the vertical plane.

2.3.1.3 Launch Geometry Computer

A missile on being fired is launched from the launcher pad,such that it always crosses the LOS to the target at a fixed short distance R_o away from the launcher after a specific time. Guidance of the missile is enabled only after this instant. To enable such launching, the launcher pad is servo-slaved to the sight-arm of the missile-pilot through an analogue computer,which computes the correction angles,

both in elevation and in bearing, in real time and adds them algebraically to the sight-arm angles of elevation and bearing. The launch geometry computer also incorporates angular corrections for:-

(i) Parallax error due to the displacement of the Director with respect to the launcher.

(ii) Wind velocity and direction

(iii) Gravity drop

(iv) Missile ballistics

These angular corrections, as shall be seen in the next Chapter, prove to be important for analysing and simulating the missile kinematics due to initial conditions.

2.3.2 Launcher

This acts as a mobile launching pad for the missiles, and is unmanned at the time of firing. It is usually positioned at a certain specified distance from the director (within allowable tolerances) along the direction of the most likely approach for the hostile aircraft (Refer Fig. 2.3) The launcher is servo-slaved in bearing and elevation to the missile-pilot's LOS through the launch geometry computer, which adds the corrections as already explained.

The launcher ceases to have any significant role after the take-off of a missile although it still remains servo-slaved to the LOS. This fact helps in engaging the same target or another target immediately by another missile, soon after the previous engagement is over.

2.3.3 Missile

The missiles used in purely defensive role, are usually subsonic to allow sufficient time for guidance. Some salient features of its propulsion, aeroframe, roll stabilization, warhead and fuses, guidance and control, arming and self destruction are briefly described below.

2.3.3.1 Propulsion

The forward propulsion is obtained by a two stage solid propellant rocket motor. The Booster stage accelerates the missile to its coasting speed ($\simeq$ 200 m/sec.) in a short time ($\simeq$ 1 sec.). The sustainer stage provides sufficient thrust to overcome drag and wind friction to maintain a uniform coasting speed for a specified period ($\simeq$ 16-20 sec.). The interception of the target is estimated to take place earlier than this.

The tail and of the missile also carries flares which enable the missile to be seen at long distances.

2.3.3.2 Aeroframe

The aeroframe consists of a streamlined cylindrical structure with conical nose, four cruciform swept-back types of control surfaces and four constant chord fixed fins set at 45° to the control surfaces. The two control surfaces in vertical plane control the yaw movements and the other two in the horizontal plane control the pitch

movement of the missile.

The yaw control surfaces are preset such that for zero command guidance there is a lift of 1 g to overcome the gravitational effect . The yaw control surfaces also carry a printed notch- cavity type of antenna for guidance commands.

2.3.3.3 Roll Stabilization

The exhaust gases of the booster motor are vented out through canted nozzles so as to provide an anti-clockwise roll movement to the missile initially for imparting stability to the missile movement. After the booster burn-out , a cordite-driven displacement gyroscope stabilizes the position of the missile in space and thereby fixes the pitch and the yaw axes of the missile.

2.3.3.4 Warhead and Fuzes

Usually, blast type of warhead is used in the nose assembly, which can be detonated by Electrically Initiated Explosives (EIE) by any/all of the following types of fuzes:

(i) Contact fuze- In the nose of the missile for direct impact.

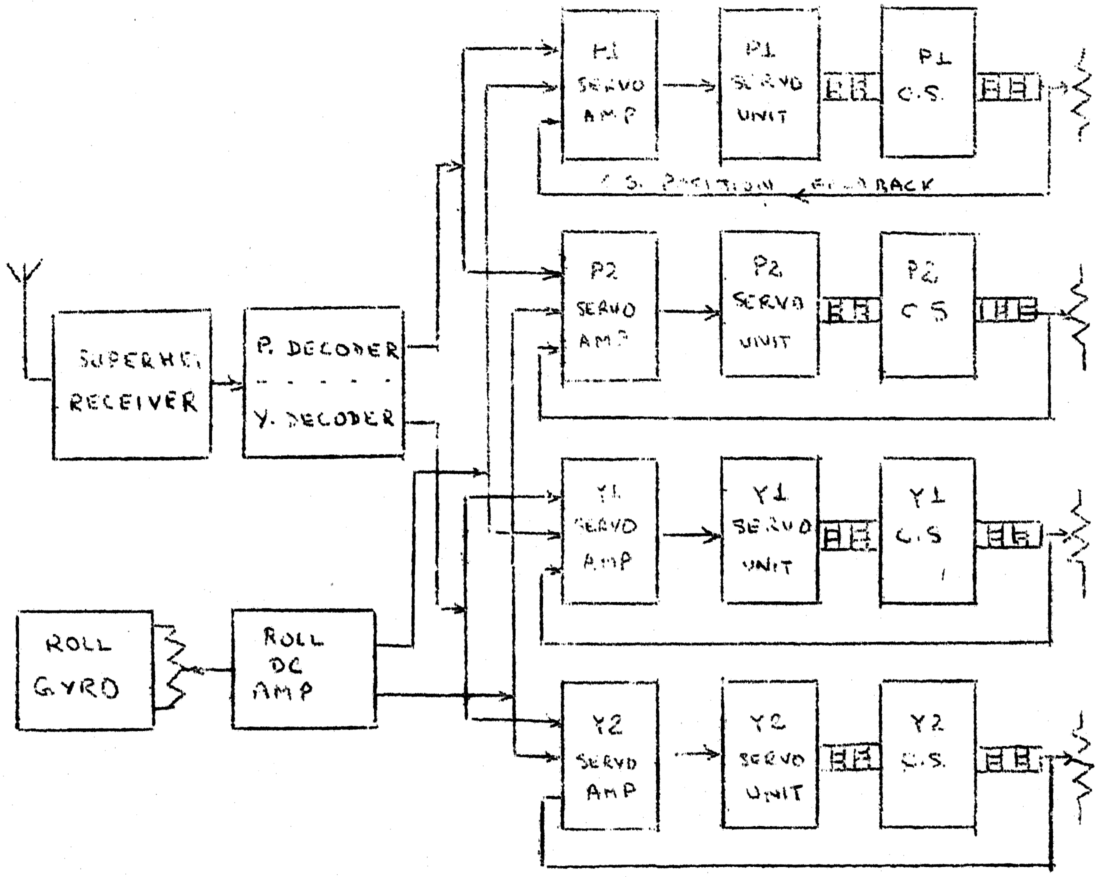
(ii) Graze Fuze - On the entire periphery of the missile particularly the control -surfaces.

(iii) Infra-red Proximity Fuze- Based on Carbon-monoxide radiation from the exhaust of the target.

2.3.3.5 <u>Guidance and Control</u>

The missile is controlled in flight by movement of the control-surfaces which are rotated by the position control electro-hydraulic servo-units in the missile. The hydraulic power for the servo-actuators is supplied from an accumulator which is pressurised by the rocket motor gases.

Fig. 2.6 gives a block diagram of the guidance and control channel in the missile. The command guidance signal from the ground equipment are picked up by the antenna, fed to a superhet receiver, decoded to regenerate up-down and right -left commands in the pitch and yaw planes, and are fed to the respective servo-amplifiers. The servo amplifiers also receive signals from the roll-gyroscope for roll stabilization. The output of the servo-amplifiers drives an electro-mechanical actuator,which operates a slide-valve to control the flow of hydraulic fluid to one piston or the other of a double acting jack,to move the control-surface shafts appropriate to the control demands. The analogue position of the shafts is fed back to the servo-amplifiers (by potentiometers) to complete the feed-back loop. The servo-amplifiers output is such that for all alterations to course or height, both control surfaces on the same plane are displaced in the same direction. For roll stabilization, the control surfaces



notes: 1 P_1 P_2 are the Control surfaces in Pitch plane.

2 Y_1 Y_2 are the Control surfaces in YAW plane

3. The Roll-gyro paraphase outputs are applied differentially to the same plane control surfaces

4 C.S ⟹ Control-surface

FIG 2.6 BLOCK DIAGRAM — GUIDANCE AND CONTROL IN MISSILE

in each plane are displaced differentially so as to produce a counter torque.

2.3.3.6 Arming and Self-destruction

For reasons of safety, the missile warhead does not get armed before a specified period (4-6 secs.) after launch. It destroys itself after a certain time (30-40 secs.), if no successful interception has taken place.

CHAPTER III

ANALYSIS AND MATHEMATICAL MODELLING OF THE GUIDANCE SYSTEM

The aim of this chapter is to carry out analysis of the command guidance and control loop and its effect on the Missile Kinematics with a view to :

(a) Comprehend the functions of each sub-block,

and (b) Deduce mathematical models in terms of transfer-functions for subsequent simulation.

3.1 APPROACH

Because of the very inherent military significance of the subject, there is little openly published literature or text available. However, based on personal experience with a system of the type and having had access to its maintenance manuals, the author has been able to adopt the following approach:-

(a) Wherever available, the circuits used in the actual equipment; were analysed and inferences drawn.

(b) The same circuits were also analysed by analogue simulation on Digital computer using PACTOLUS software package. This led either to the

verification of the results obtained analytically or to the deduction of results for which analytical solution was found difficult. This technique has been intensively used.

(c) From the data available from the manuals, analytic expressions have been determined by using the curve-fitting techniques.

Again, strictly on grounds of security restrictions; the details of analysis based on actual equipment circuits has not been considered discrete to be published in this thesis. However, a summary of the deductions obtained in all such case studies has been brought out, in general terms.

3.2 REVIEW OF GUIDANCE AND CONTROL BLOCK

From the study of the Command-link transmitter and the guidance and control used in the missile, as presented in the previous chapter; it is seen that the FC commands result in proportional angular rotations of the control-surfaces of the missile with some time-constants involved. The units which contribute to the time constants are:

(a) Command shaping which consists of range compensation, modulus limiting and synthetic rate damping (SRD)

(b) Missile servos.

The FC, the supply frequency filter, sub-modulator and the RF command link between the ground equipment and the missile are not expected to contribute any significant delay.

The angular movements of the control-surfaces about their axes produce aerodynamic forces resulting in accelerations of the missile, which can be resolved along the longer axis (the forward thrust axis) and the lateral axis of the missile. It is the lateral acceleration which is of significance as that will result in rate components of angular velocities in the respective planes and cause the missile kinematics to change the attitude and the flight trajectory of the missile.

Thus, the complete guidance and control loop can be generalized into a block-diagram as shown in Fig. 3.1.

From this, it becomes clear that for simulation of the guidance and control system; mathematical modelling is required for the following:-

(a) Command shaping (including range-compensation, modulus-limiting and SRD)

(b) Missile servos

(c) Aerodynamics of the missile

(d) Kinematics of the missile.

For better comprehension of the system, it is necessary to study the missile kinetics also. The subsequent sections, therefore, discuss missile kinetics first, followed by missile kinematics, command shaping, missile servos and the aerodynamic transfer-functions.

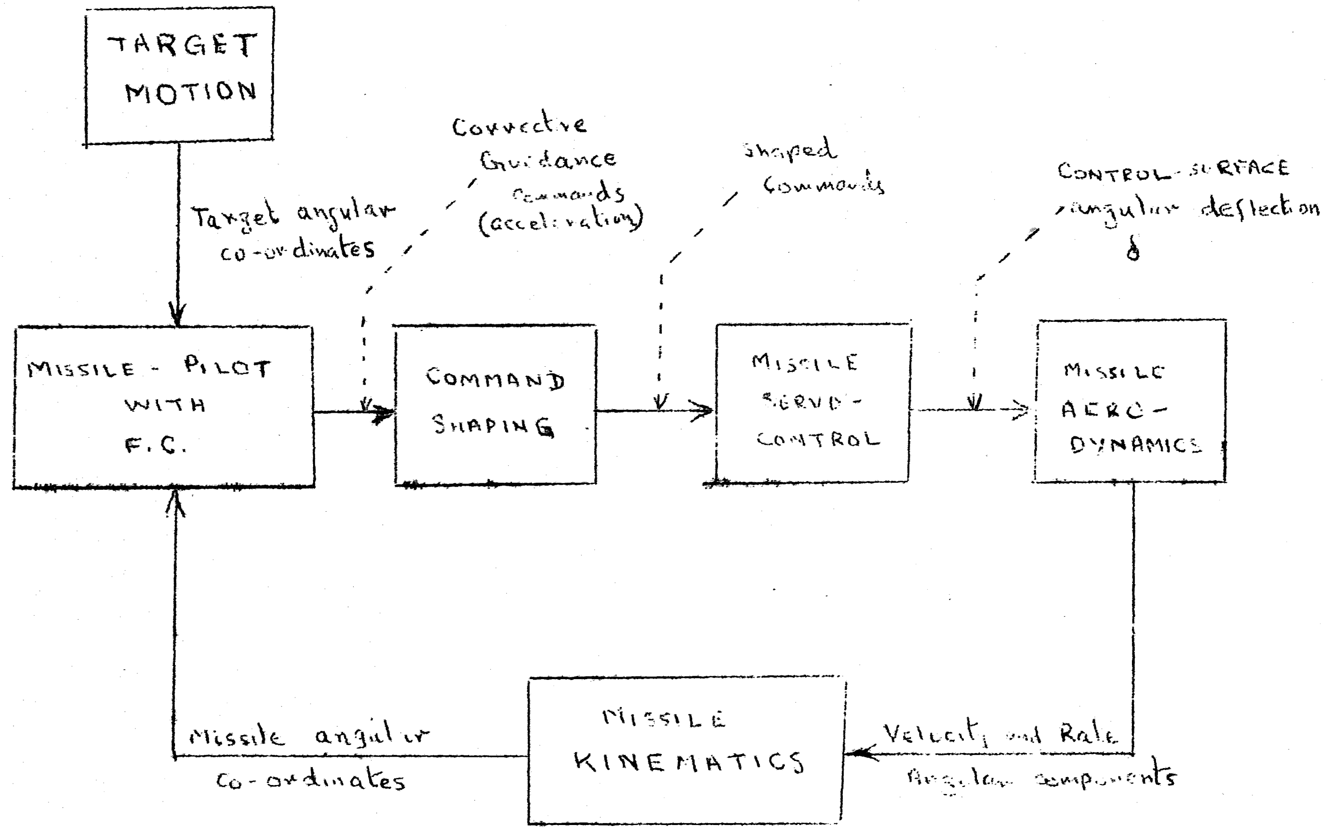


FIG 3.1 GENERALIZED GUIDANCE AND CONTROL LOOP

3.3 MISSILE KINETICS

If the relevant system parameters and the data for the rocket motor thrust, the weight of the missile, the rate of combustion of the rocket-motor propellant are known; the complete dynamics of the missile i.e. its acceleration, velocity and range (as functions of time) can be computed by the analogue solution of the standard differential equation

$$\frac{W(t)}{g} \cdot a_F = F(t) - W(t).\sin E_L - K.V_M^2 \qquad (3.1)$$

where $W(t)$ - Instantaneous weight of the missile taking rate of fuel combustion into account.

a_F - Forward acceleration of the missile as a function of time t.

g - Acceleration due to gravity

$F(t)$ - Forward thrust of the motor

E_L - The angle ~~in~~ of elevation at which the missile is launched.

V_M - Instantaneous missile speed

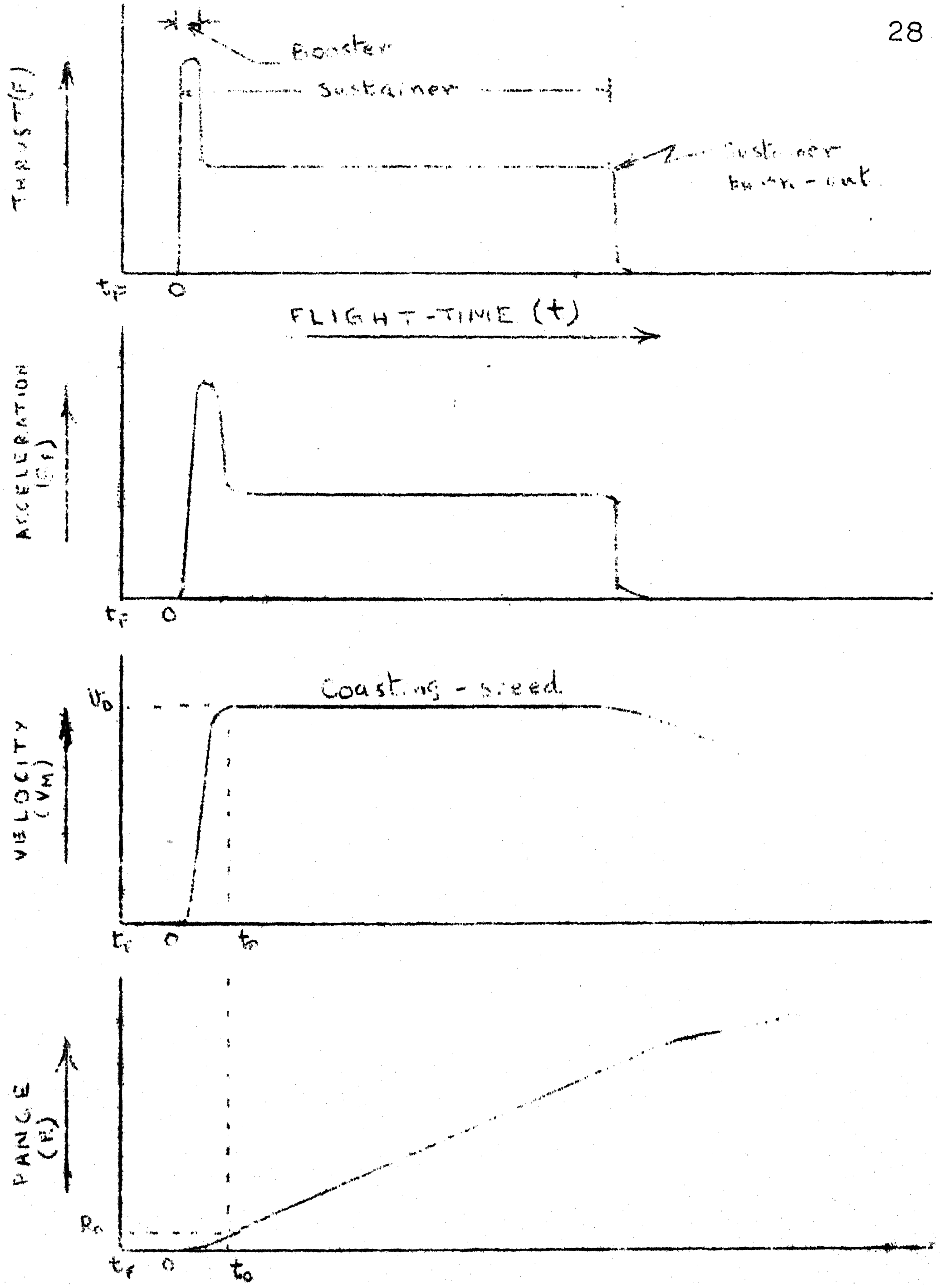
and K - Co-efficient of aerodynamics resistance.

A case study was actually carried out, using the data available for a particular system, by an analogue simulation of the differential equation on IBM 7044 using PACTOLUS software package. Data was generated for the acceleration, velocity and range of the missile upto 20 secs. Further,

to obtain an analytic linear expression for the instantaneous range of the missile (R); curve-fitting technique (using least squares method) was resorted to by using the data generated for the range at various instants of time. The data for the instantaneous missile velocities led to the computation of the average velocity 'u' of the missile over the entire flight time (20 secs.)

The qualitative nature of the characteristic curves obtained for the acceleration, velocity and range, corresponding to a typical rocket-motor thrust characteristic are depicted in Fig. 3.2. The same characteristics can be generalized to be attributable to any other similar missile also.

It is to be expected that the duration of the booster and the sustainer stages of the rocket-motor, are significant parameters for determining the other system parameters. For instance, the stabilizing time t_o and the corresponding range covered R_o during this period (refer Fig. 3.2) influence the launch geometry of the missile, as shall be seen subsequently in this chapter. The missile velocity remains almost uniform after time t_o till the sustainer stage burns out, After this, the velocity begins to taper down due to the aerodynamic resistance. It is interesting to note that the missile is always fired such that the missile crosses the line-of-sight to the target at distance



t_F - Instant Firing-trigger is pressed.

0 - Instant missile is fired (Origin t-axis)

FIG 3.2 NATURE OF MISSILE - KINETICS

R_o after time t_o ; and it is only after this instant that the missile guidance is enabled.

The range characteristic is almost linear during the coasting phase and can be approximated by expression

$$R \simeq u.t \tag{3.2}$$

where R is the range of the missile and u is the average speed computed over the entire normal flight time. A more exact approximation is obtained by using the linear expression.

$$R = v_o(t-t_o) + R_o \tag{3.3}$$

where v_o is the missile coasting speed.

This relationship has also been verified by the curve fitting technique mentioned earlier.

3.4 MISSILE KINEMATICS AND ITS COMPONENTS

The missile-pilot perceives the relative motion of the missile with respect to the target in space, as the angular displacement between their instantaneous positions. Since at long ranges, the perception of depth is difficult, despite the binocular vision; the perception is essentially of the angular displacements projected on a 2-dimensional plane, which is normal to the missile-pilot's line of sight (LOS) and is referred to as the VIEWING-PLANE (viewing plane will be defined more precisely in the next section).

The missile-kinematics consists of:-

(a) Kinematics due to the initial launch velocity and direction,

(b) Kinematics due to the relative motion of the missile with respect to a moving target, keeping the position of the target fixed in the viewing plane, and

(c) Kinematics due to the guidance commands.

Each of these contributory factors are studied under mutually exclusive conditions in the next three sections.

3.5 MISSILE KINEMATICS DUE TO INITIAL LAUNCH CONDITIONS

Fig. 3.3 depicts 3-dimensional geometrical layout for the initial missile launch conditions. In the diagram, d represents the distance between the Director and the Launcher in the ground plane; and h' is a relative height assigned to the Director in order to compensate for the gravity-drop at the instant of missile take-off.

As mentioned in Chapter II, the missile is launched at a bearing B_L and elevation E_L such that it always crosses the LOS (having bearing B_S and elevation E_S) at a pre-determined fixed distance R_o from the launcher in time t_o after launch. Parameters R_o and t_o are determined by the missile kinetics discussed in section 3.3. Angles B_L and E_L are, in fact , computed by the Launch geometry computer, by first computing the corresponding correction angles B_C and E_C, as already mentioned in section 2.3. Then,

$$B_L = B_S + B_C \tag{3.4}$$

and $$E_L = E_S + E_C \tag{3.5}$$

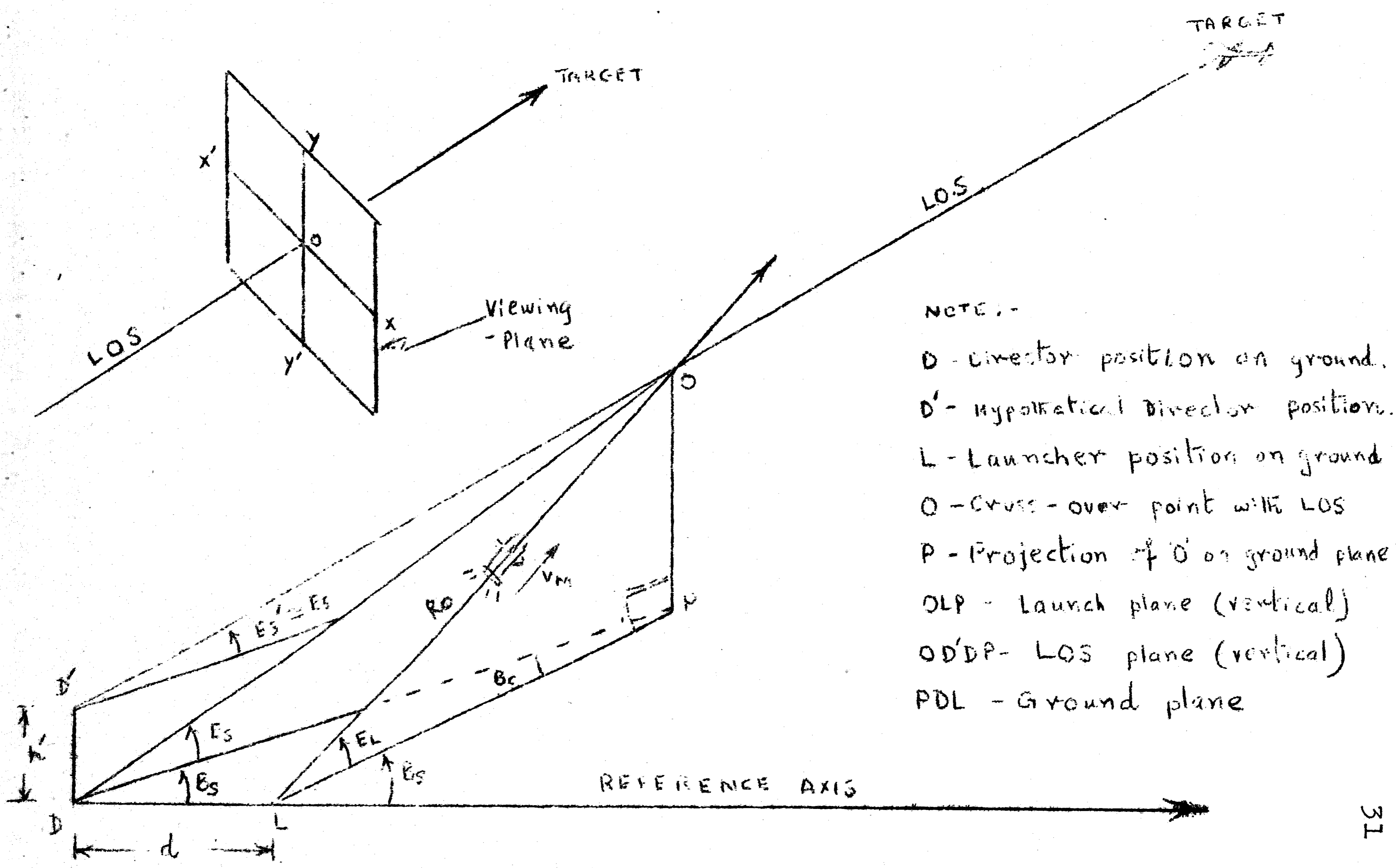


FIG 3·3 3-DIMENSIONAL GEOMETRICAL LAYOUT FOR INITIAL LAUNCH CONDITIONS

Further, the following practical assumptions are made:

(a) $d \ll R_o$

(b) $h' \ll R_o$

(c) The target is assumed to be stationary and the LOS, therefore, remains fixed. (The effect of target movement and the consequent rotation of LOS axis is discussed separately).

(d) The missile is assumed to move with a uniform velocity equal to its average value u. (This assumption is seriously in error during the early stages for $t < t_o$).

(e) E_S is small. This is true for the low-flying targets (which is a system characteristic), and particularly so for the initial conditions when the targets are picked up at long ranges.

Then from the geometry of Fig. 3.3, B_C and E_C can be shown (Appendix A) to be given by the following expressions.

$$B_C \simeq \sin B_C = \frac{d \sin B_S \sec E_L}{R_o} \tag{3.6}$$

$$E_C \simeq \frac{d \cos B_S . \sin E_S + h' \cos E_S}{R_o} \tag{3.7}$$

It follows from assumptions (a),(b) and (e) that the correction angles B_C and E_C, as computed from above expressions, shall in reality be of small magnitude.

To consider the missile kinematics due to these launch conditions, the expressions for linear and angular velocity components and the consequent missile angular co-ordinates projected on to the viewing-plane shall be determined in the subsequent sub-sections. The viewing-plane as mentioned earlier, is the plane on which the missile-pilot perceives the two dimensional relative positions of the target and the missile through his binocular sight, and is as such normal to the line of sight to the target as shown in Fig. 3.3.

It is convenient, at this point, to denote the two vertical planes OLP (containing missile launch trajectory) and OD'DP (containing LOS to the target) by LAUNCH-PLANE and TARGET-PLANE respectively. The apparent horizontal movement of the missile in the viewing plane is along the normal to the target-plane, and its, apparent vertical motion is along the perpendicular to the LOS to the target in the target-plane. The relative motion of the missile with respect to the target in the viewing plane can therefore be resolved along these two directions, indicated by X-axis and Y-axis respectively in Fig. 3.3 (inset).

3.5.1 <u>Linear Velocity Components</u>

Referring to Fig. 3.3, the speed of the missile attained is constant value v_0 when it reaches the crossover point 'O' (ref. Fig. 3.2) in the launch plane. The exact analysis for

the velocity components in the viewing plane, passing through O is given in Appendix 'B'. An approximate analysis, justified by the assumption that, B_C being small, the launch plane can be considered to coincide with the target plane ; is given below with the help of the simplified diagrams of Fig. 3.4.

In the vertical plane, the velocity components along and perpendicular to the LOS , and hence along the Z and Y axes of the viewing-plane, are:

$$v_z \simeq v_o . \cos E_C \tag{3.8}$$

and $$v_y \simeq v_o . \sin E_C \tag{3.9}$$

From the horizontal plane, the x-component in the viewing-plane is obtained as

$$v_x \simeq v_o . \cos E_L . \sin B_C \tag{3.10}$$

The missile will appear to move in the viewing-plane, from right to left (and hence V_x is negative) for $\sin B_S > 0$, and from left to right (correspondingly V_x is positive) for $\sin B_S < 0$. It should be noted that all these components are constant, throughout the flight of the missile by virtue of the initial assumptions.

3.5.2 Angular Velocity Components

The corresponding angular velocity components are obtained by dividing the respective linear velocity

components by the instantaneous range R of the missile, which is a time dependent function, as given by Eqn. (3.3).

(a) Angular velocity component along x- axis

$$w_x = \frac{v_x}{R} = - \frac{V_o \cdot \cos E_L \cdot B_C}{R_o + v_o \cdot \cos E_C \cdot (t-t_o)}$$

Substituting for B_C from (3.6), and considering $\cos E_C \simeq 1$ (E_C being small),

$$w_x = - \frac{V_o \cdot \cos E_L \cdot [d \sin B_S \cdot \sec E_L]}{R_o [R_o + V_o \cdot (t-t_o)]}$$

or $$w_x \simeq - \frac{V_o \cdot d\sin B_S}{R_o[R_o + V_o \cdot (t-t_o)]} \qquad (3.11)$$

(b) Angular velocity component along y-axis

$$w_{y1} = \frac{v_{y1}}{R} \simeq \frac{V_o \cdot \sin E_C}{R_o + V_o \cdot \cos E_C \cdot (t-t_o)}$$

Substituting for E_C from (3.7), and considering $\cos E_C \simeq 1$, and $\sin E_S \simeq E_S$

$$w_{y1} = \frac{V_o \cdot \sin \left[\frac{h' + d \cdot \cos B_S \cdot E_S}{R_o}\right]}{R_o + V_o \cdot (t-t_o)}$$

Since the argument of the sine term is small, this

$$w_{y1} \simeq \frac{V_o}{R_o + V_o.(t-t_o)} \left[\frac{h' + d\cos B_S . E_S}{R_o} \right] \quad (3.12)$$

3.5.3 Missile Angular Co-ordinates

Since the angular co-ordinates are zero at $t = t_o$; the instantaneous angular co-ordinates, θ_x and θ_y in the viewing-plane are given for $t \geqslant t_o$, as follows:

$$\theta_x = \int_{t_o}^{t} w_x . dt$$

$$= - \frac{V_o d\sin B_S}{R_o} . \int_{t_o}^{t} \frac{dt}{R_o + V_o (t-t_o)}$$

$$= - \frac{d \sin B_S}{R_o} . \ln\left[\frac{R_o + V_o(t-t_o)}{R_o}\right]$$

or $$\theta_x = - \frac{d \sin B_S}{R_o} \ln.\left[1 + \frac{V_o}{R_o} (t-t_o)\right] \quad (3.13)$$

and similarly,

$$\theta_{y1} = \int_{t_o}^{t} w_{y1} . dt$$

or $$\theta_{y1} = \frac{h' + d\cos B_S . E_S}{R_o} . \ln\left[1 + \frac{V_o}{R_o} (t-t_o) \right] \quad (3.14)$$

3.5.4 SUMMARY AND INFERENCES

The results obtained in this section are summarized and inferences drawn from these are mentioned below:

(a) Components of the linear velocity are functions of the correction-angles B_C and E_C, which are

determined by the initial conditions of the target bearing and elevation at the time of missile launch. Since B_C and E_C are normally small ; the magnitude of the components of the velocity in the viewing-plane is small and remains constant throughout the flight period.

(b) The corresponding components of the angular velocity decrease with increase in time. The magnitude and sign of w_x are dependent on the initial target bearing B_S alone; whereas w_{y1} is always positive (for targets above the ground level) and its magnitude depends on the target bearing and elevation both. However, since E_S is usually small (low flying targets), it follows from expression (3.12) that w_{y1} can be considered to be practically independent of both the target elevation and the bearing.

(c) The angular positions of the missile vary as the logarithmic functions of time . Apart from this dependence on time; θ_x is primarily a function of target bearing B_S, and θ_{y1} is essentially a function of h'/R_o and is practically independent of both B_S and E_S.

These deductions will be useful in the next chapter for development of a simulation model.

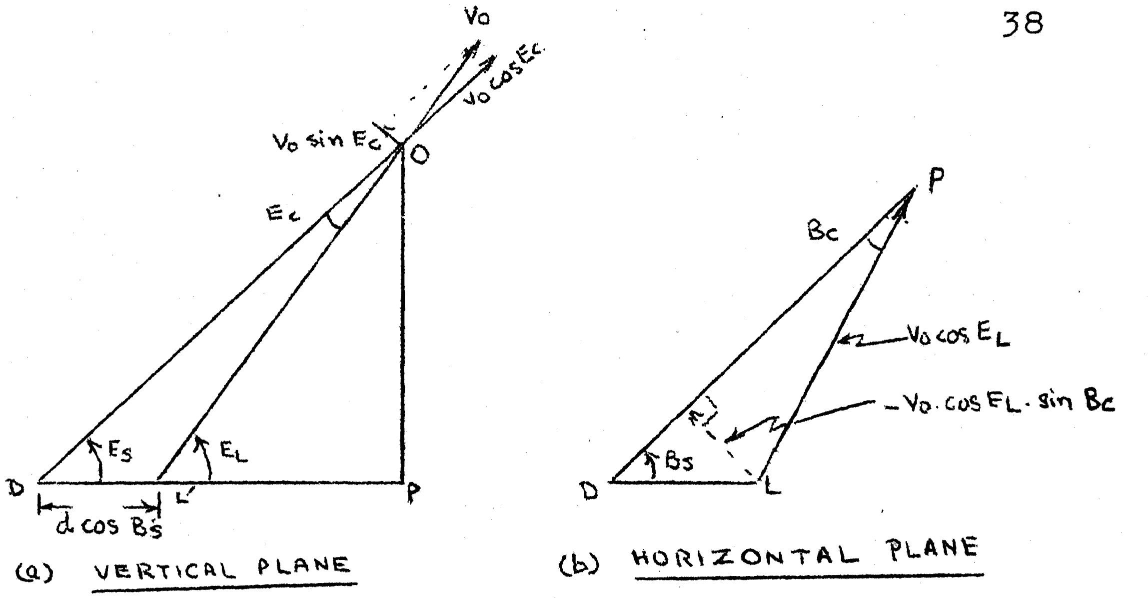


FIG 3.4 SIMPLIFIED DIAGRAMS — LINEAR VELOCITY COMPONENTS

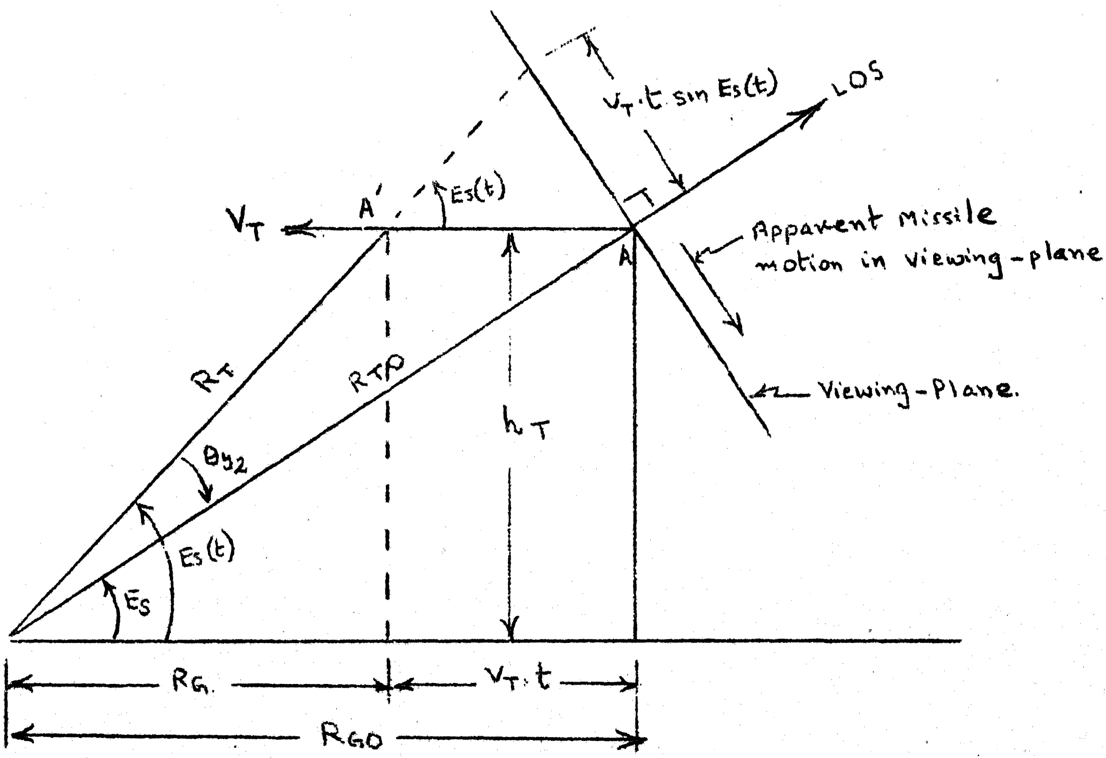


FIG. 3.5 RELATIVE MISSILE MOTION DUE TO TARGET MOTION. (VERTICAL PLANE)

3.6 RELATIVE MISSILE KINEMATICS DUE TO TARGET MOTION

The target is assumed to move with a uniform speed V_T at a constant height h_T directly towards the direction of the Director. Since the system characteristics, as defined in Chapter II, are such that only directly approaching targets are normally tackled in a defensive role, the effect of other target courses is ignored for the present analysis. Thus, the consideration is simplified to the plane vertical to the ground, containing the LOS and the target, as shown in Fig. 3.5. The effect in the horizontal plane, due to the assumed constraints, shall be insignificant.

Qualitatively, it is obvious that the approaching movement of the target will appear on the 2-dimensional viewing-plane as if the target is climbing up. However, due to the fact that the target position is always maintained approximately at the centre of the viewing-plane, either manually by the missile-pilot or by a servo-slaved system of the sight-arm to a tracking radar locked on to the target; the LOS consequently moves up in elevation with the target's forward movement, to maintain the target in the centre of view; and relatively the missile appears to be moving down in the viewing-plane.

To have a quantitative assessment of this apparent downward motion of the missile; reference is made to

Fig. 3.5, which shows a typical geometrical layout of the target movement in relation to the Director (and hence the missile-pilot) in the vertical plane.

Let A be the initial position of the target(origin of the corresponding viewing-plane) at the time of launching the missile (t=0) and E_S, R_{TO}, R_{GO} and h_T be its corresponding angle of elevation, slant range , ground-range and relative height with respect to the Director on the ground plane. At a later instant of time t, the target moves to position A' such that the LOS then makes an angle $E_S(t)$ with the horizontal and R_G and R_T become the corresponding ground and slant ranges respectively.

The missile-pilot will thus perceive relative missile-motion on the viewing-plane as angular displacement of the missile position as

$$\theta_{y2} = - [E_S(t) - E_S]$$

From the geometry of Fig. 3.5,

$$\theta_{y2} = - \tan^{-1} \frac{V_T . t . \sin E_S(t)}{R_{TO}}$$

Assuming E_S to be small ,θ_{y2} can be expressed as

$$\left.\begin{aligned} \theta_{y2} &= - \tan^{-1} \frac{V_T . E_S . t}{R_T} \\ \text{or} \quad \theta_{y2} &= - \tan^{-1} \frac{V_T . E_S . t}{[h_T^2 + (R_{GO} - V_T . t)^2]^{\frac{1}{2}}} \end{aligned}\right\} \quad (3.15)$$

Also the apparent angular velocity of the missile in the viewing-plane

$$w_{y2} = \frac{d}{dt}(\theta_{y2})$$

$$\simeq - \frac{V_T \cdot h_T}{h_T^2 + (R_{GO} - V_T . t)^2} \qquad (3.16)$$

This can be expressed as

$$w_{y2} \cong - \frac{E_S}{t_d} \cdot \frac{1}{E_S^2 + (1 - t/t_d)^2} \qquad (3.17)$$

where $t_d = R_{GO}/V_T$ represents the initial range of the target expressed in seconds.

Inferences

From the expressions derived above, the following deductions are made:-

(a) The relative angular velocity of the missile along the vertical axis of the viewing-plane, for a particular target speed V_T, initial elevation E_S and initial range R_{GO} ; increases as the target approaches, tending to a maximum value

$$w_{y2_{max}} \doteq - \frac{V_T}{R_{GO} . E_S}$$

This maximum value occurs when the target flies directly overhead.

(b) For typical target speeds and altitudes of attacking aircraft, the rate of apparent missile descent in the field of view is determined essentially by the initial target elevation E_S at which the missile is launched. This fact is significant from the point of view of simulating the missile behaviour.

3.7 CASE STUDY FOR MISSILE KINEMATICS OF A TYPICAL SYSTEM (EXCLUDING GUIDANCE)

To have a quantitative asssement of the results obtained so far, a case study for a typical system was carried out under a set of presumed typical target parameters. The results obtained by analysis so far, were used to compute the missile angular velocities and positions (using the approximations) individually for the effect of initial conditions and the relative target movement in the vertical plane, and then were combined to get the overall effect. Table 3.1 gives a summary of the computations for missile flight time 0-20 seconds.

Fig. 3.6 gives the graphical representation of the angular velocities and Fig. 3.7 shows the angular position of the missile on the vertical plane of the viewing-plane (without any guidance commands being given).

TABLE 3.1 SUMMARY OF COMPUTATIONS-MISSILE KINEMATICS DUE TO INITIAL CONDITIONS AND RELATIVE TARGET MOTION (VERTICAL PLANE) (CASE STUDY)

<table>
<tr><th>FLIGHT-TIME
't' (secs.)</th><th>TARGET GROUND-RANGE
R_G (KMs)</th><th>w_{y1}
(rad/sec.)</th><th>w_{y2}
(rad/sec.)</th><th>w_y
(rad/sec.)</th><th>θ_y
(radians)</th></tr>
<tr><td>0</td><td>7.99</td><td rowspan="2">0.048</td><td>-0.0014</td><td rowspan="2">0.047</td><td>-0.094</td></tr>
<tr><td>2</td><td>7.39</td><td>-0.0016</td><td>0.0</td></tr>
<tr><td>4</td><td>6.79</td><td>0.022</td><td>-0.00195</td><td>0.021</td><td>0.068</td></tr>
<tr><td>8</td><td>5.59</td><td>0.011</td><td>-0.0029</td><td>0.008</td><td>0.126</td></tr>
<tr><td>12</td><td>4.39</td><td>0.0073</td><td>-0.0047</td><td>0.0026</td><td>0.147</td></tr>
<tr><td>16</td><td>3.19</td><td>0.0054</td><td>-0.00875</td><td>-0.0034</td><td>0.1456</td></tr>
<tr><td>20</td><td>1.99</td><td>0.0043</td><td>-0.02</td><td>-0.016</td><td>0.106</td></tr>
</table>

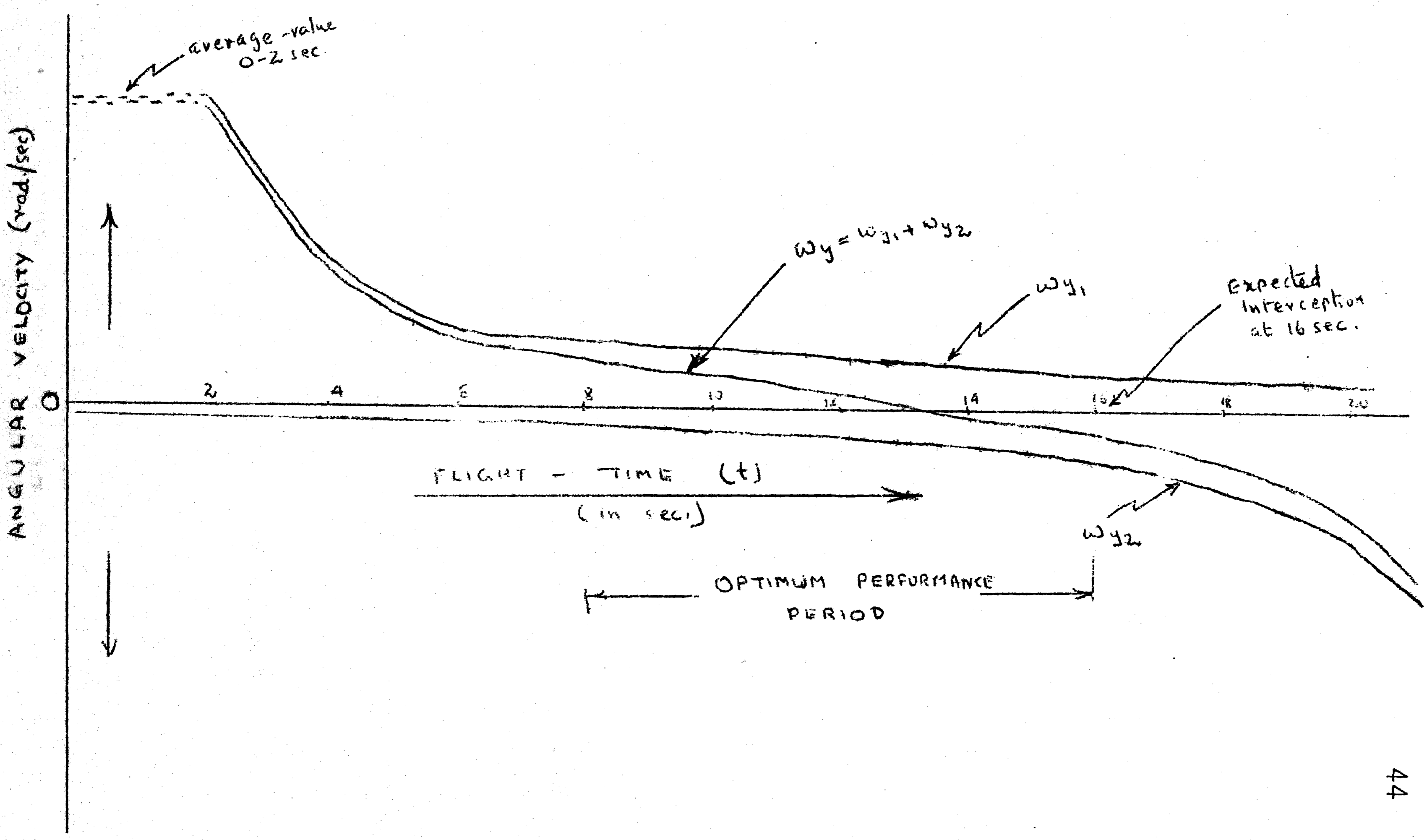


FIG. 3.6 MISSILE ANGULAR VELOCITIES DUE TO INITIAL CONDITIONS AND RELATIVE TARGET MOTION. (VERTICAL PLANE) (CASE - STUDY)

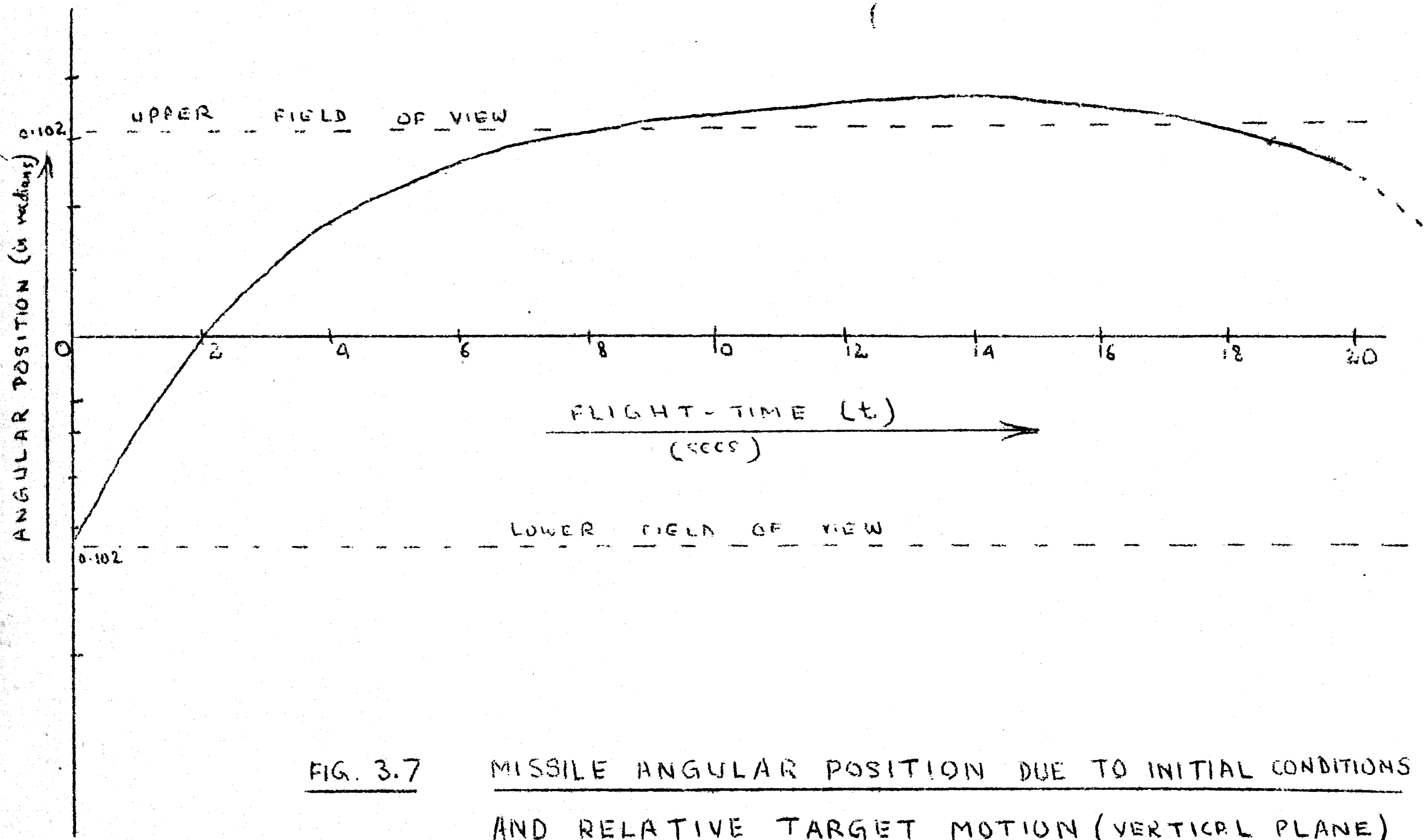


FIG. 3.7 MISSILE ANGULAR POSITION DUE TO INITIAL CONDITIONS AND RELATIVE TARGET MOTION (VERTICAL PLANE)

(CASE STUDY)

The following set of parameters have been presumed (based on an actual weapon system):

Target

Target speed (V_T) = 300m/sec.

Target height (h_T) = 300m.

Target range at time of fire = 8KM.

Corresponding initial target elevation E_S = 2.1^o

Target bearing B_S = 0^o.

(The target is assumed to approach directly along the azimuth reference axis i.e. the most likely and expected direction of approach).

Missile

Speed (v_o) = 200m/sec.

Missile speed is assumed uniform between period 2-16 sec. of flight time.

Ground-equipment

Distance between the Director and the Launcher

$$d = 75 \pm 25 \text{ ft.}$$

Gravity-drop correction $h' = 87$ ft.

Missile-LOS crossover distance $R_o = 1000$ ft.

Crossover time $(t_o) = 2.0$ sec.

A perusal of graphical representation in Figures 3.6 and 3.7 unveils the following significant inferences:-

(a) Due to the initial conditions, the missile angular velocity in the vertical plane is substantially high

in the beginning, and reduces almost exponentially to a modest rate.

(b) The effect of target movement on missile angular velocity is insignificant in the early stages and remains so for considerable period. However, its effect becomes the predominant factor during the later stages of flight. It is obvious that if the target is picked-up flying at higher altitude or less range, the curve corresponding to the target motion effect will shift to the left.

(c) The resultant angular velocity due to the combined effects of the initial conditions and the target movement is such that it reduces initially at a rapid rate (upto $\simeq$ 8 secs.), maintains a constant rate for a certain period (upto 16secs.) and then starts reducing again rapidly under the influence of target motion.

(d) In the field of view, the missile-pilot,(if he were not to apply any guidance signals), will perceive the missile entering/climbing his view from the bottom in the vertical plane, and moving initially at a very rapid rate, cross his LOS (the centre of the binocular graticule) at +2 seconds after launch, continue to move up at a progressively reducing rate ($\simeq$ exponential), stay steady at the peak value for a while and commence moving down the field of view at a progressively increasing rate.

(e) The effect in the x-plane is expected to be similar except that the effect of relative target movement will NOT be there as the target is assumed to be directly approaching (NOT being a crosser target.)

(f) Some interesting and very significant deductions are drawn from para (c) above for the optimum guidance and system performance. Guidance of the missile to the target LOS is difficult as well as critical during the first 8 secs. of missile launch (known as the GATHERING PHASE). If a missile -pilot has 'gathered' the missile on to his LOS during this phase, then maintaining it in coincidence with the LOS thereafter is relatively easy upto 16 secs., after which again the guidance will become difficult. Thus, a very important conclusion that can be drawn is that <u>it is the gathering phase guidance which the missile-pilot must be intensively trained for</u>.

Moreover, the target must be picked up early but a missile should be fired <u>only</u> at the optimum range (8KM in this case) so that the interception takes place between 10-16 secs. after launch for ideal system performance. Early/late firing of missile, both situations create conditions for difficult guidance and require higher calibre of skill and acumen from the missile-pilot for a successful engagement.

The importance of the deductions drawn particularly for para (f) above is that the results obtained tally exactly with the tactical performance guidelines given in the literature of the classified actual weapon system, based on which the case study was carried out.

This fact is assuring and validates the analytic results obtained (including approximations taken) so far.

3.8 MISSILE KINEMATICS DUE TO GUIDANCE

The missile-pilot senses the angular error between his LOS to the target and to the missile both in the pitch and the yaw planes, and applies corrective commands through the FC (again both in pitch and yaw), which effectively deflect the respective control-surfaces of the missile appropriately to produce aerodynamic forces such as to produce lateral accelerations in the respective planes. Since the control in the two planes, pitch and yaw, is identical and independent of each other, a general analysis valid for both planes will be taken up. The analysis is being carried out for zero initial-conditions.

The lateral acceleration 'a' in polar coordinates (R,θ) is given by the standard differential equation as

$$a = \frac{R.d^2\theta}{dt^2} + 2.\frac{dR}{dt}\cdot\frac{d\theta}{dt} + \frac{d^2R}{dt^2}.\theta$$

Since the forward acceleration of the missile during the coasting phase is zero,

$$\therefore \quad \frac{d^2R}{dt^2} = 0$$

Hence $$a = \frac{R.d^2\theta}{dt^2} + 2.\frac{dR}{dt}.\frac{d\theta}{dt}$$

$$= R.\dot{w} + 2\,uw$$

where $\dot{w}$ - angular acceleration

w - angular velocity

and u - average velocity $\simeq \frac{dR}{dt}$

$$\text{or} \quad \dot{w} = \frac{a-2uw}{R} \tag{3.18}$$

Substituting $R \simeq ut$ in the above equation, the same can be expressed as a linear differential equation

$$\dot{w} + (2/t).w = a/(ut)$$

The solution of this equation yields

$$w = \frac{1}{ut^2}.\int_{T_1}^{t} a.t.dt. \tag{3.19}$$

where T_1 is the time at which acceleration command 'a' is applied . The acceleration command may be of the nature of a step-input or a time varying function.

Equation (3.19) establishes the relation between the lateral acceleration produced by the control-surfaces of the missile and the angular velocity sensed by the missile-pilot in either plane, pitch or yaw.

The command signals applied by a human operator are intrinsically of the nature of a train of randomly applied

steps; which(presuming that no range-compensation is incorporated in the signal processing) will generate corresponding step accelerations (lateral) in the missile. Thus, the kinematic response to such type of acceleration commands is of interest, and are analysed further.

3.8.1 Kinematics Response to a Step Input Command.

Considering **a simple case,** where a single step 'a' is applied at time $t = T_1$ and presuming that no command was given prior to this,

$$w = \frac{1}{ut^2} . \int_{T_1}^{t} a.t.\, dt = \frac{a}{2u} . \left[1 - \frac{T_1^2}{t^2}\right] \qquad (3.20)$$

The normalized angular velocity [$w/(a/2u)$] **is shown** plotted in Fig. 3.8 for various values of T_1 during the normal flight period . The characteristics of the response can be summarized as follows:

(a) The initial value at $t=T_1$ is zero.

(b) The final value $w_f = a/2u$.

and (c) The rise time $t_r = 2.1T_1$

Thus, the rise-time is a dependent function of T_1, the time of application of command and hence the range of the missile at that time.

Looking at the problem from the point of view of the missile-pilot, he sees a different kinematic response for the same command at various stages of the missile flight. The

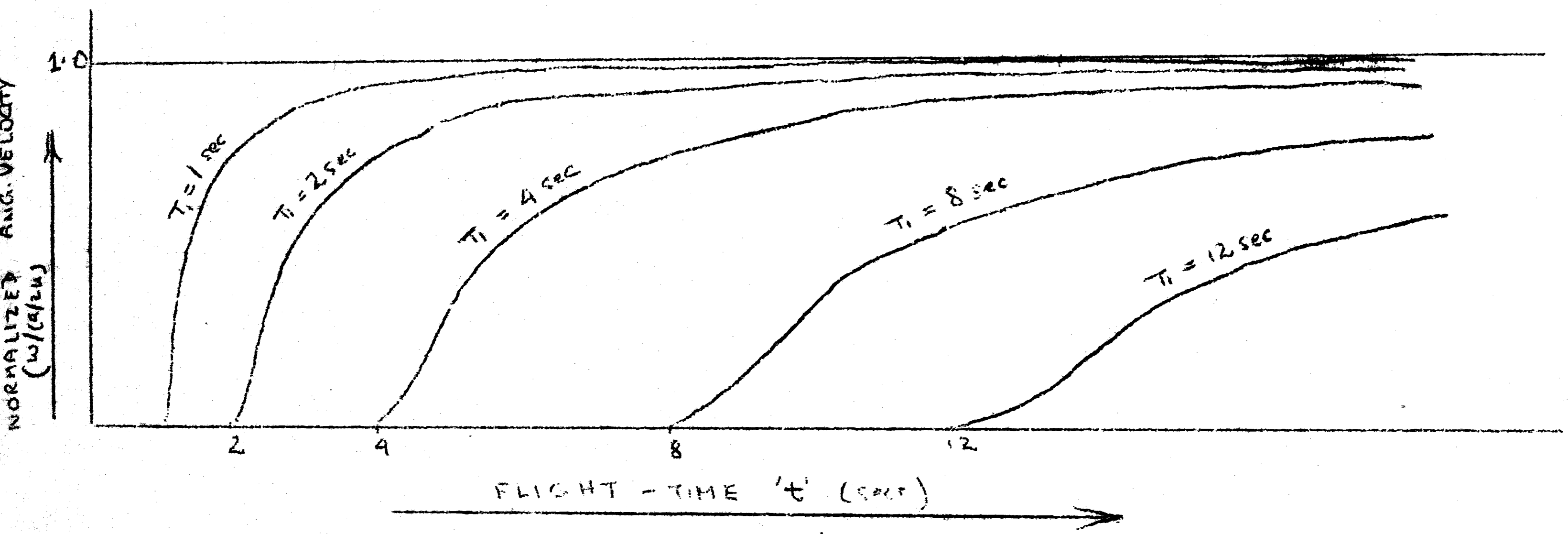


FIG 3.8 ANGULAR VELOCITY DUE TO GUIDANCE COMMANDS AS FUNCTION OF T_1

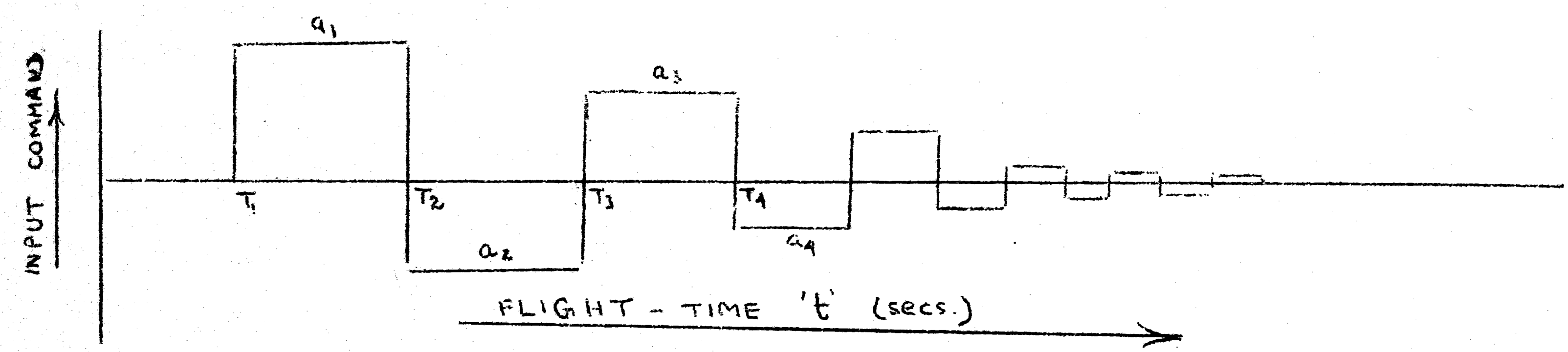


FIG. 3.9 RANDOM NATURE OF STEP-INPUT COMMANDS APPLIED BY MISSILE-PILOTS DURING GUIDANCE

response becomes progressively sluggish as the time of flight or the range of the missile increases.

3.8.2. Kinematic Response to a Series of Step Inputs

In previous sub-section, a simple single command step-input was considered. In reality, however, the missile-pilot shall be applying a series of random pulses as shown in Fig. 3.9 . There may be occassions, particularly at long ranges, when the steady-state w due to the previous input step has not been achieved and the next step is applied. In such cases, the initial value of w shall significantly affect the response.

(a) Case assuming steady state 'w' is achieved before application of next command

Considering the first two steps applied at $t = T_1$ and $t = T_2$, then from equations (3.19) and (3.20), for $t \geqslant T_2$

$$w = \frac{a_2}{2u} + \frac{c}{t^2} .$$

With the initial-condition that

$$w = a_1/2u \text{ at } t = T_2,$$

$$c = - \frac{\delta a}{2u} \cdot T_2^2$$

where $\delta a = (a_2 - a_1)$ and 'c' is a constant of integration, and hence

$$w = \frac{a_2}{2u} \cdot [\, 1 - \frac{\delta a}{a_2} \cdot \frac{T_2^2}{t^2} \,] \text{ for } t \geqslant T_2$$

Thus, in general

$$w = \frac{a}{2u} \cdot [\, 1 - \frac{\delta a}{a} \cdot \frac{T^2}{t^2} \,] \tag{3.21}$$

where a - current command step input at $t = T$

and δa - step change in command at time $t = T$.

(b) <u>Case assuming steady-state is NOT achieved</u>

Then,

$$w = \frac{a_1}{2u} \cdot \left[1 - \frac{T_1^2}{t^2} \right] \text{ for } T_1 \leq t \leq T_2$$

and

$$w = \frac{a_2}{2u} + \frac{c}{t^2} \quad \text{for } t \geqslant T_2$$

where $c = - \frac{1}{2u} \cdot \left[a_2 - a_1 \left(1 - \frac{T_1^2}{T_2^2}\right) \right] . T_2^2$

Hence $w_2 = \frac{a_2}{2u} . \left[1 - \frac{T_2^2}{t^2} . \left(1 - \frac{a_1}{a_2} . \left(1 - \frac{T_1^2}{T_2^2}\right)\right)\right]$

In general,

$$w = \frac{a}{2u} \cdot \left[1 - \frac{T^2}{t^2} \left(1 - \frac{a'}{a} \left(1 - \frac{T'^2}{T^2}\right)\right) \right] \quad (3.22)$$

where a - current command step applied at $t = T$

and a' - previous command step applied at $t = T'$

Thus, the kinematic response in reality and the most general case becomes more complex.

3.9 COMMAND SHAPING-RANGE COMPENSATION

Necessity

As brought out in the inferences of section 3.8.1, the missile-pilot senses different kinematic behaviour of the missile for the <u>same</u> command at different stages of missile flight. The response becomes progressively sluggish as the time of flight/ range of the missile increases. This

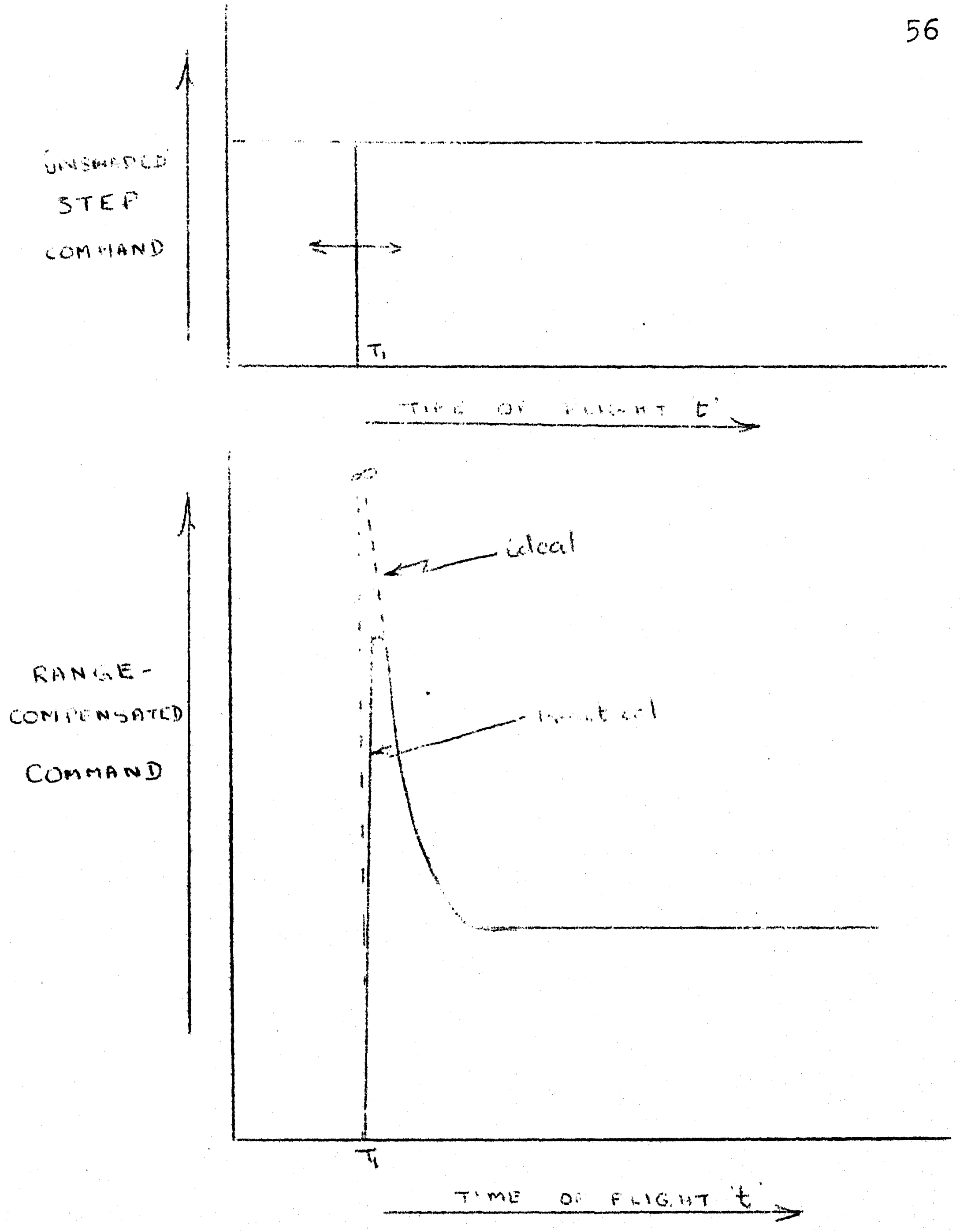


FIG 3.10 NATURE OF COMMAND SHAPING REQUIRED FOR RANGE-COMPENSATION

Practical Limitations for Ideal Realization

Ideal range compensation is difficult to realize because of the problems of amplifier saturation and the requirement of time varying gain of the amplifier. Generally, compensation is provided for the most critical period of guidance i.e. the gathering phase, and a fixed compensation is given for the subsequent period. Thus, there is always some uncompensated element and there is a lag in the missile response, though at a much reduced scale.

Case Study for Range Compensation

To have quantitative assessment of the technique used and to evaluate its effectiveness for range compensation; the hardware used in an actual system has been studied, both analytically as well as by simulation (PACTOLUS) on IBM 7044; in conjunction with the kinematic equation. First, the case-study for range compensation alone is discussed.

3.9.1 Case Study-Range Compensation Alone

Small signal analysis was carried out for the range compensation circuitory used in a particular guidance system. The output e_o corresponding to a step-input E_i applied at $t=T_1$ is given by

$$e_o = - \frac{50.E_i}{1 + 100[1-(1-m).e^{-\frac{200}{3}.m(t-T_1)}].[1-(1-n).e^{-20n(t-T_1)}]} \tag{3.27}$$

'm' and 'n' are real numbers, whose values decrease in discrete steps upto the system gathering time and then remain constant. (In the actual system, this is achieved by increasing the time-constants of two RC low-pass filters, in a step by step manner. The low-pass filters constitute the feed-back loop of a DC amplifier having a fixed gain of 50.)

The following inferences are drawn from expression (3,27):

(a) The initial value e_{oi} of the output at $t=T_1$ is given by

$$e_{oi} = - \frac{50.E_i}{1+100\ mn} \tag{3.28}$$

Since the values of 'm' and 'n' are determined by time T_1; the initial magnitude of the output is determined by the amplitude of the command input and

the time T_1 it is applied.

(b) The maximum value of the output is attained at $t=T_1$. This implies that the initial value is also the maximum value.

(c) The final value of the output, e_{of} is given approximately by

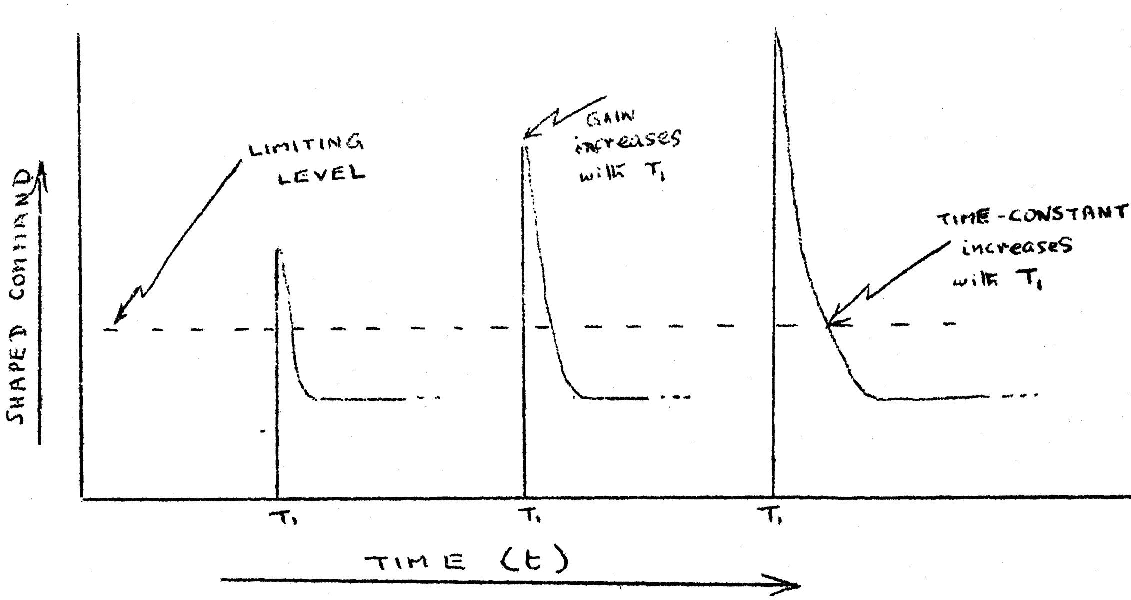
$$e_{of} \simeq - E_i/2 \quad (3.29)$$

This implies that the final value of the output settles down to half the value of the input command.

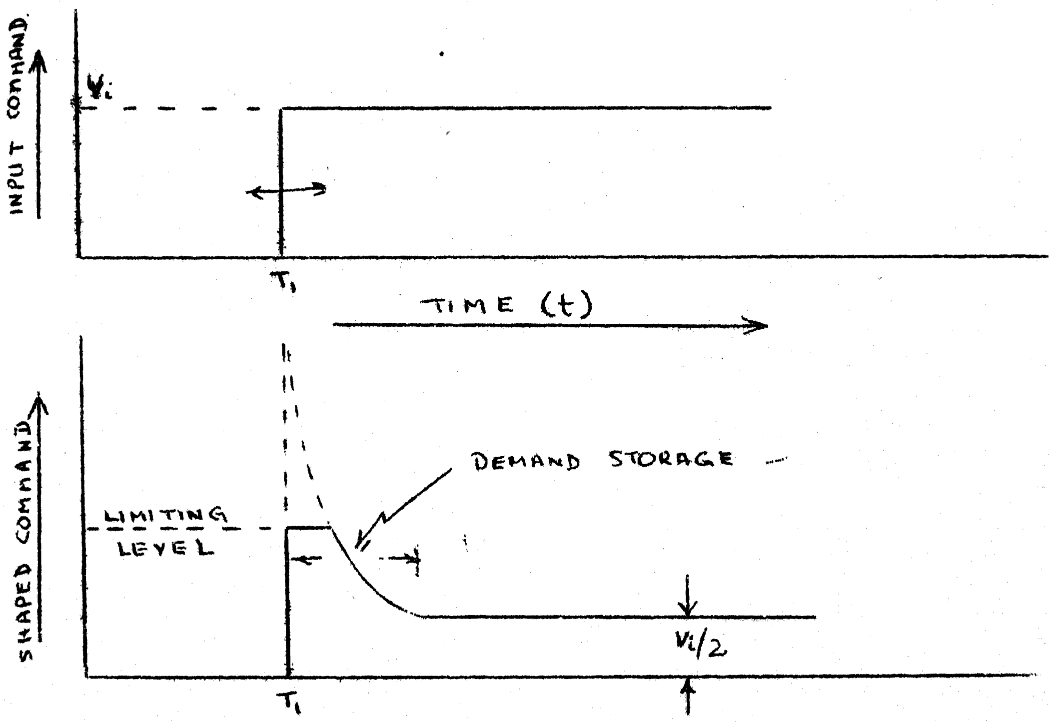
(d) The output, during the intervening period between the initial value and the final value, is exponential in nature with its time-constant increasing with time, due to the variation in values of m and n.

To verify the above analytical deductions, step-input response of the range-compensation unit was studied by computing the values of e_o for different values of E_i applied at different values of T_1 from expression (3.27), by using techniques of both FORTRAN IV programming and simulation by PACTOLUS software package. The qualitative nature of the response obtained is shown in Fig. 3.11(a). The effect of limiting the output, (as is done in the actual hardware) is also depicted in the same figure, and separately in Fig. 3.11(b).

The part of the response marked as 'DEMAND STORAGE', (which in effect it practically represents) is clearly a



(a) STEP COMMANDS APPLIED AT DIFFERENT VALUES OF T_1



(b) EFFECT OF LIMITING

FIG 3.11 COMMAND SHAPING FOR RANGE-COMPENSATION (CASE-STUDY)

function of the amplitude, and the instant of application of the step-input command.

Thus, the nature of the range-compensated output conforms to the general qualitative requirements, outlined earlier and deduced from the kinematics behaviour of the missile.

3.9.2 Case Study-Effect of Range Compensation on Missile Kinematic Behaviour

The case study was further extended to study the effect of range compensation, as implemented in the hardware of an actual system, on the kinematic behaviour of the missile.

The general kinematic equation as derived in section 3.8 was

$$w = \frac{1}{ut^2} \cdot \int_{T_1}^{t} a.t.dt. \qquad (3.19)$$

The acceleration "a" in the above expression, after shaping for range-compensation, is a time-varying function determined by the output computed from expression (3.27).

By substituting expression (3.27) for a(t) in (3.19) (ignoring the effect of intervening missile servos and the aerodynamic function), and using approximate analysis, it was found that the resulting angular velocity 'w' consisted of infinite series of terms, which can be

combined together as follows:-

$$w = \frac{1}{2} \begin{bmatrix} \text{Normal Kinematic} \\ \text{Response due to} \\ \text{'unshaped' command} \end{bmatrix} + \begin{bmatrix} \text{Infinite series of} \\ \text{compensation terms} \\ \text{as } f\ (T_1, t) \end{bmatrix}$$

The factor $\frac{1}{2}$, (introduced by virtue of Eqn. (3.29)) is insignificant, as apparently it is taken care of by a gain of 2 in the missile-servos. The compensation terms consist of infinite series of exponential expressions, with reducing amplitude; and are determined by the instantaneous values of 'm' and 'n', referred to earlier; and are therefore, functions of T_1 and t.

Thus, the kinematic response of the shaped acceleration commands is the normal response to the unshaped commands, to which compensation is added as function of T_1 and t.

To validate the above analytical results; the earlier PACTOLUS simulation for range compensation was coupled with the analogue model for the kinematic expression, and the response for various values of V_i applied at different instants of time T_1, was obtained. The results conformed to the analytical results. A salient feature, which emerged as a result of the simulated study, was that the compensation was never complete. It only improved the kinematic response by reducing its lag. Moreover, the amount of compensation deteriorated as the time T_1 was delayed.

3.10 COMMAND SHAPING FOR MODULUS LIMITING

The aim of modulus limiting has already been explained in qualitative terms in Chapter II. Referring to Fig. 3.12, the circle in the transverse plane represents an ideal modulus-limiter. The shaded area represents the analysed permissible range for the acceleration commands under modulus limiting in the same actual existing system, as already mentioned.

3.11 AERODYNAMICS TRANSFER-FUNCTION

No endeavour has been made in the present study to go into details of the aerodynamics involved. The results quoted in a classified literature have been taken for granted. In any case, quantitative case study is not feasible in absence of data for the profile cross-section of the control-surfaces.

In general, the input-output relationship in terms of lateral acceleration produced per unit angular deflection of control surface is taken as

$$H_a(s) = H_{ao} \frac{1 + K_3 s + K_4 s^2}{1 + K_1 s + K_2 s^2} \qquad (3.30)$$

where H_{ao} is the d-c gain and K_1, K_2, K_3 and K_4 are real co-efficients determined by aerodynamic factors, and are such that they produce two pairs of complex zeros and poles. The complex poles determine the natural

frequency of the missile.

3.12 COMMAND LINK AND MISSILE SERVOS

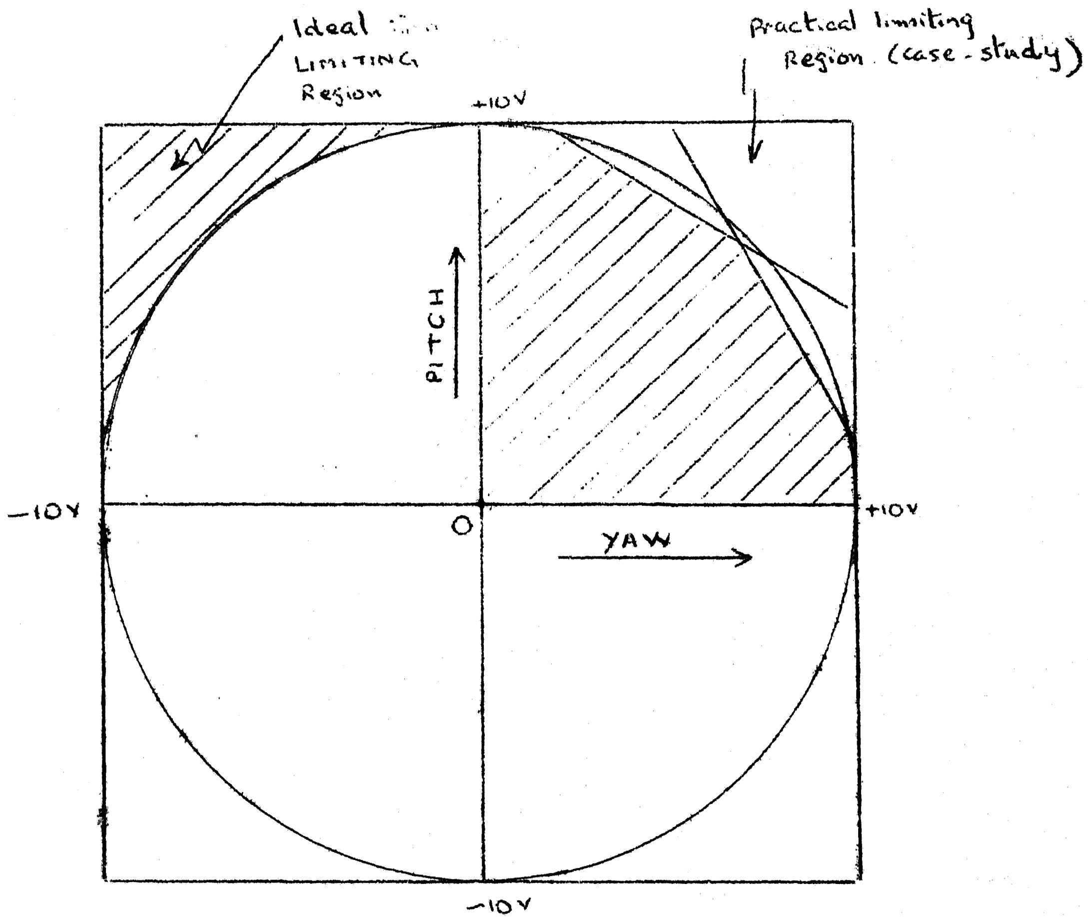
The guidance and servo-control system has already been described briefly in Chapter II. The electro-hydraulic system generally used for the position control of the angular rotation of control surfaces will produce two time-constants, such that the transfer function giving the angular deflection of the control surfaces per unit input command to the servo-amplifier is of the form

$$H_s(s) = H_{so} \frac{1}{(1 + K_5 s)(1 + K_6 s)} \tag{3.31}$$

where H_{so} is DC gain of the system. K_5 and K_6 are the time-constants determined by the components of the electro-hydraulic system. As only qualitative details of the servo-system were available, no detailed analysis for a case study could be carried out.

3.13 COMMAND SHAPING FOR SYNTHETIC RATE DAMPING (SRD)

As mentioned earlier, to avoid lateral rate gyro in the missile; the command signals are shaped in the ground equipment such that at frequencies equal to or in vicinity of the weather-cock/natural frequency of the missile, the response is dampened. The importance of SRD becomes significant as the weather-cock frequency



Note :- PRACTICAL LIMITING SHOWN IN ONE QUADRANT ONLY

FIG 3.12 MODULUS - LIMITING

of the missiles, as determined by the poles of $H_a(s)$ given by Eqn. (3.30), is of the range 2-4 Hz, and the thumb movement of the missile-pilot to produce commands can excite these frequencies during guidance. A notch-filter is usually used to achieve the simulated effect of rate gyro.

The general form of the required T.F. is as follows:

$$H_{SRD} = \frac{1 + K_1 s + K_2 s^2}{1 + K_7 s + K_8 s^2} \tag{3.32}$$

Since frequencies in vicinity of weather-cock frequency are also required to be dampened, therefore $\alpha = 1/Q$ need not be large, making the circuit less critical.

Case Study for Synthetic Rate Damping

The circuitry used in the ground equipment was analysed. A DC amplifier with high gain is used with RC filters in the input and feed-back circuits. The T.F. of this, is given by

$$H(s) = \frac{1 + .014s + .0029s^2}{1 + .092s + .0028s^2} \tag{3.33}$$

This gives $f_c \simeq 2.9$c/s, which tallies with the value specified in the literature for the equipment. α is calculated to be 0.87 for this.

3.14 COMBINED SRD AND AERODYNAMIC TRANSFER-FUNCTION

As discussed in sections 3.11 and 3.13, the natural frequency of the missile is determined by the poles of $H_a(s)$; and in fact, the complete numerator term of the SRD T.F. is the same as the denominator term of the aerodynamic T.F.; it is thus possible to combine the two to take advantage of the cancellation to give a combined T.F.

$$H_{COMB}(s) = H_{ao} \cdot \frac{1 + K_3 s + K_4 s^2}{1 + K_7 s + K_8 s^2} \tag{3.34}$$

This enables simplification in the simulation model.

CHAPTER IV

SIMULATION CONSIDERATIONS AND MODELLING

Having acquired a general background knowledge, supported by mathematical analysis, of command guided weapon systems; the present and the subsequent chapters go on to tackle the primary objective of the study i.e. to design, develop and fabricate a suitable training-aid for the simulated training of missile-pilots.

The present chapter discusses the fundamental simulation problem and its qualitative requirements, followed by consideration of various factors which influence the nature of the intended training device. The chapter then goes on to explore in detail the alternative simulation schemes of individual functional ingredients of the complete systems, by considering the relevant factors, their approximations where applicable and the consequent logical deductions. Possible techniques for hardware realization have been indicated, wherever they were considered relevant. It is towards the end of the chapter that a clear picture of a feasible overall simulation model emerges. This simulation model is recommended for ultimate development and adoption into service. A laboratory model, based on a limited portion of the

proposed model, has been successfully designed and fabricated ; and is discussed in the next chapter.

4.1 FUNDAMENTAL SIMULATION PROBLEM

The objective of the present study is focussed on the training aspect of the missile-pilot i.e. to enable him to acquire and improve his standard of proficiency, in his task of guiding the missile in flight on to a target successfully, without actually firing a missile. The main simulation to be performed is, therefore, that of the missile behaviour under guidance control. In addition, it may also be necessary to produce a synthetic target, in case a live target is not readily available. The simulated missile and the synthetic target have to be displayed visually by some means, and obviously the depiction can be achieved by two distinct spots of light. Clearly, the training-aid will then consist of two major units:-

(a) Simulator Unit:- This will compute and generate analogue instantaneous co-ordinates of the positions of the missile and the synthetic target, as projected on to a 2 dimensional viewing-plane of the missile-pilot.

(b) Display Unit:- This will depict the relative angular positions of the missile and the target by means of two spots of light, moving under control of the

respective analogue voltages generated in the simulator unit.

Before going into the details of these two units, some qualitative requirements and considerations affecting the nature and type of the intended training device shall be discussed.

4.2 GENERAL QUALITATIVE REQUIREMENTS

Some of these are obvious and are true for any training-aid based on simulation techniques. However, a few of these are listed below:

(a) Simulation must be realistic. It is not only the functional realism, which of course, is essential; environmental realism is equally important. The environmental factors include the position and posture of the trainee, his surrounding equipment, noise-level, ambient weather conditions, state of physical and emotional stress levels normally encountered under actual battle conditions.

(b) The training-aid should inherently cater for progressive levels of training. (These are discussed in next section).

(c) Facility for assessment or performance evaluation of the trainee, both qualitatively and quantitatively, is desirable.

(d) The device must be simple to operate. It must be portable, rugged, reliable and should require minimum periodic/preventive maintenance. In general, it should conform to the usual qualitative requirements common to all military hardware.

(e) Concepts of standardization and universality of equipment should be incorporated as far as possible.

4.3 CONSIDERATION OF FACTORS INFLUENCING THE NATURE OF TRAINING DEVICE

The following factors are considered relevant in influencing the nature of the training device:-

(a) Progressive nature of training.

(b) Desirability of having a universal type of training-aid.

(c) The extent to which ground-equipment can be associated for simulated training.

(d) Use of live targets vs. synthetic targets.

These are discussed in the following sub-sections.

4.3.1 Progressive Nature of Training

The training of missile-pilots is envisaged at three levels:-

(a) Basic Phase

This is for the fresh recruits to get the 'feel' of the flight-controller displacements in relation to the

simulated missile response.

The training device for this phase can be used for testing the aptitude and hence for selection of personnel to the cadre of missile-pilots, in addition to their subsequent basic training to improve aptitude and skill to a basic minimum level.

The training-aid for this phase need not be accurate and oriented for any particular weapon system. For instance trainees intended for different systems (belonging to the same class) can be trained on the same training-aid. The training-aid for this phase is envisaged to be inherently an indoor (class-room) type of device.

(b) Advanced Phase:

This is for a particular system-oriented training with/without using the ground equipment. This phase of training is visualized to be carried out at the training centres in continuation of their basic preliminary training, before being posted to the field units.

The training-aid for this phase has to be more realistic to the actual system and precise to the system characteristics.

(c) Field Phase:

This phase is for 'on job' training of missile-pilots while serving with active field units. The training is

meant to be a continuation training for

(i) Keeping the reflexes sharp,

and (ii) Improvement in skill under actual operating conditions.

This phase of training should be carried out with the ground equipment and possibly with live-targets, where possible.

4.3.2 Universal Nature of the Training Device

From the foregoing discussion, it may appear that three types of training-aids are required to be developed corresponding to the three levels of training standards. However, on grounds of standardization and economy; it is desirable to have a universal nature of the training-aid so that any one of the three modes corresponding to the training levels can be selected. The three modes may be designated as:

(a) Basic/Learner training mode (L)

(b) Advanced training mode (A)

(c) Field training mode (F)

All subsequent discussion in this chapter shall be referred to by this nomenclature.

There can be an argument, for stretching the concept of standardization and universality of the training-aid further; for incorporating facility for using the same

device for training of personnel for different weapon systems belonging to the same class. This is feasible in L-mode but is not considered justified for application in A and F modes, on grounds of additional avoidable cost and complexity of the equipment. As a matter of fact, this type of universal training-aid will have little applicability, except perhaps at the training centres.

Thus, it is envisaged that the training-aid to be developed will be for a particular system only. However, it is true that a training-aid for another similar system can be easily designed and fabricated on exactly identical lines with appropriate changes in the circuit parameters (R,C values and pot-settings alone). The production engineering aspect will remain unaltered.

4.3.3 Use of Ground Equipment for Simulated Training

There are conflicting considerations for the use of ground-equipment being associated with the training-aid. Its use is desirable from considerations of:

(a) Incorporating realism

(b) Simplifying the hardware of the training device by taking advantage of the existing hardware on the ground-equipment itself.

The argument against intensive use of ground-equipment for training is from consideration of equipment life period. It is a fact that more military hardware

gets damaged or its life-time is reduced due to wear and tear in training rather than in actual combat operations.

Both the conflicting considerations seem to carry almost equal weights; and therefore it is felt that a compromise solution has to be adopted. Limited training with the actual ground-equipment cannot and should not be ruled out, and facility for using the training device with/without the ground-equipment should be incorporated. This implies that all the ground-equipment hardware, relevant to command guidance, has to be either repeated or preferably simulated in the training device for routine training in A-mode. At the same time, with suitable switching, the training-aid system should be compatible for operation with the ground-equipment in F-mode.

4.3.4 Use of Live Targets vs. Synthetic Targets

It is positively desirable to practise the missile-pilots against live-targets (from own Air-Force) using simulated missile. (The technique of doing this is outlined under display alternatives). The obvious advantages of using live targets are:-

(a) Maximum realism, particularly environmental realism, can be attained under typical combat conditions. Moreover, the entire crew associated with the organization of the weapon system, can be tactically deployed and practised

according to their respective battle -drills.

(b) The hardware for the simulator unit is simplified in that a synthetic target is not required to be generated.

The disadvantages of using live targets are:

(a) It is not always possible or convenient to arrange for practice targets.

(b) The training exercises are expensive in terms of both money and time.

(c) The display system requires a special optical unit to superimpose a light spot simulating the missile over the normal binocular field of view.

Thus, the inference drawn is that it would be desirable to use live targets, like the ground-equipment; for periodic training in the F-mode; and routine training in the A-mode should be carried out with synthetically generated targets.

Thus, the target simulation in the simulation unit becomes imperative, with facility to switch it off while operating in the F-mode.

4.4 DISPLAY SYSTEMS

The simulator unit produces instantaneous x-y co-ordinates of the angular positions of the target and the missile in terms of analogue voltages. The missile

and the target are required to be displayed in the form of two visible distinct spots of light moving under the control of the respective analogue positional outputs of the simulator unit. The display systems, therefore, has to be inherently an optical system, which can be realized in the form of either of the following:-

(a) CRT display,

(b) An optical projection system on a wide screen,

and (c) A special optical system for use with live targets alone.

Each of these alternatives are discussed below for their relative merits and demerits.

A significant fact to be noted is that in reality as the missile recedes from the pilot, it appears to be smaller in size and in brightness, while the approchhing target appears to grow in size. It is naturally desirable to incorporate this feature for effect in the Display system to bring in realism. The effect can be easily realized by the intensity modulation of the two spots of light. This implies that the analogue functions controlling the intensity modulation of the two spots representing the missile and the target, must also be generated in the simulator unit as Z-co-ordinates[These Z-co-ordinates are not to be mistaken for the usual implication of Z-co-ordinate in space]. Thus, the guidance simulator is required

to generate analogue voltages X_M, Y_M, Z_M and X_T, Y_T and Z_T corresponding to the x-y angular positions and the intensity levels of the missile and the target respectively. The generated analogue voltages are functions of time commencing from the instant of firing the missile.

4.4.1 CRT Display

In principle, a Cathode-Ray Tube with a large screen such as a TV picture tube, can be used. The x-y co-ordinates can be fed to two identical channel-amplifiers having the same gain, appropriate for full utilization of the screen space. The screen graticules can be calliberated in terms of angular measure per unit analogue voltage applied. The screen then represents the field of view of the missile pilot. Alternatively, a CRO can also be used conveniently with the advantage of the built-in channel amplifiers. The respective target and missile co-ordinates can be multiplexed by chopping, and the multiplexed outputs can be fed as the X_{CRO}, Y_{CRO} and Z_{CRO} inputs to a single beam CRO in x-y mode of operation This would result in two spots corresponding to the target and the missile positions, and the Z_{CRO} produces the desired intensity modulation of the two spots. (This scheme has been actually implemented, and its details are given in Chapter V).

Thus, an inter-face unit comprising of a multiplexer is required for CRT display. The interface for CRT display shall require identical channel amplifiers as well. The advantages of this type of display are:

(a) It is simple in principle;

(b) There is minimum complexity of interface-hardware and hence easy to fabricate,

(c) It is relatively inexpensive. (Any low-cost low-frequency single beam oscilloscope can be used),

(d) It is ideally suited for indoor training.

(e) No elaborate setting-up arrangements or a specially designed room is required.

The disadvantages of using CRT display are:

(a) The maximum distance that a trainee can be made to sit away from the CRT screen, is limited; and it is unlikely that a binocular sight. can be used to view the scope screen. This fact steals away considerable realism, although all other remaining factors for environmental realism can be produced/simulated.

(b) Due to the relatively small size of the screen and the consequent reduced scale for the normal field of view, the target position deviations from the centre of the field of view are small during manual target tracking. (This problem is

discussed further under target simulation). In effect, the trainee is not practised in tracking the target and endeavouring to keep it in the centre of the field of view; which in reality, he is required to do simultaneously with the task of guidance control; provided the system is NOT slaved to a tracking radar.

From the above discussion, it is clear that the CRO/CRT display is suitable only for the basic phase of the training (L-mode), or at most for the early stages of Advanced training phase.

Another application for this type of display can be with field units strictly as a refresher or a reflex - sharpening aid for the missile-pilots, for indoor training on bad weather days.

4.4.2 Optical Projection Display

This system can be visualized to be using a large screen/wall, on which a slide representing typical sky conditions can be projected to create environment.

The missile-pilot under other normal environmental conditions (of position, seat etc.) views the screen through his binocular sight. The X,Y,Z co-ordinates generated in the simulator unit are fed to two independent optical units, one each for the missile and the target.

These two optical units project two distinct spots of light which are superimposed over the background scene; and move in accordance with the analogue voltages produced by the simulator under the guidance commands as applied through the F.C.

The advantages of this system are:

(a) It is realistic as both the disadvantages of the CRT display system are overcome to a large extent.

(b) It provides an indoor training facility, with synthetic targets.

The disadvantages are:

(a) The hardware required is relatively complex and elaborate.

(b) It requires special setting up of a room; and renders the system as a static installation, and therefore, makes it unsuitable for training in field.

Hence for intensive and advanced level of training (A-mode) , this system seems to be the ideal for use at the training centres.

4.4.3 Optical System For Use With Live Targets

In this system, it is envisaged that the missile is simulated by a spot of light, which is superimposed on the binocular field of view of the missile -pilot such that the missile-pilot will see the actual live target and a spot of light simulating the missile movements in behaviour and in response to the F.C. demands.

The relative merits and demerits of this system have already been discussed under section 4.3.4.

This type of display system is suited for training in field, where there is a possibility of availability of live targets (e.g. locations near own air-fields); and at the same time where the facilities for optical projection display cannot be made available.

4.5 TARGET SIMULATION

The relevant parameters of a target for generation of synthetic target-trajectories are its range, speed, bearing and elevation.

Target simulation is to be considered separately for the initial values of the parameters at the time of launch, and the dynamic values during the encounter.

4.5.1 Simulation for Target Initial Conditions

The initial values of the target bearing and elevation at the time of firing the missile are important for determining the missile-kinematics behaviour due to the initial launch conditions. (Reference section 3.5). The range and the speed of the target, at the time of missile launch, determine the Engagement Time. The Engagement time is the approximate time-interval between the instant of missile-launch and the time the missile and the target are likely to intercept. If the target is directly approaching without manoeuvring,

then,

$$\text{Engagement time} \simeq \frac{R_{TO}}{V_T + v_o}$$

where R_{TO} is the initial target slant range, and v_T, v_o are the respective target and missile speeds.

Thus, the initial value settings of the target bearing and elevation are essentially linked with missile simulation; while the target initial range and its speed, in terms of engagement time, are important for the timing and control functions in the simulator unit.

The initial values for the target bearing, elevation and the engagement time can be conveniently set with front-panel potentiometers in hardware realization.

4.5.2 <u>Simulation for Target Dynamic Conditions</u>

While considering target simulation under dynamic conditions, the following aspects are to be kept in mind:-

(a) The target motion in space is perceived as its projection on a 2-dimensional viewing plane (as defined earlier in Chapter III).

(b) The LOS of the missile-pilot follows the target; and with ideal tracking, the target should be seen always at the centre of the field of view, in almost immobile state. However, due to inherent inconsistencies in the manual tracking of the

target, the target will appear to be moving around the centre of the field of view. Even if the sight-arm is slaved to a tracking radar, locked on to the target, the target will practically never appear to be stationary at the centre of the field of view.

(c) With passage of time, as the target approaches, it appears to increase in size.

(d) The target simulation under dynamic conditions is influenced by the nature of display system used. As discussed earlier in section 4.8.1, the CRO display gives little opportunity for practising target tracking. Consequently , only limited random movement of the simulated target on the scope around the centre of the screen is required to depict the target motion during the engagement period.

However, with the optical projection type of display, target tracking is possible; and it is desirable to simulate common likely target trajectories (as projected on to the 2-dimensional viewing plane).

In either case of display, the target trajectory simulation can be effected by feeding analogue voltages corresponding to the instantaneous X_T, Y_T positions of the target (with reference to the x-y axes) from a pre-programmed tape. A number of recordings can be made for typical

likely trajectories, which can cater for various standards/ levels of training and the types of display used (i.e. the CRO display or the optical projection type).

Alternatively, approximate and yet effective simulation can be achieved by the manual control of the target position by the Instructor, through two potentiometers (for the pitch and the yaw movements) on the front-panel of the simulator. In fact, the instructor can consider himself to be the pilot of the attacking aircraft and play the 'war game' with the trainee to impart advanced training for tackling manoeuvring targets.

The increasing size of the target, with passage of time during the engagement, can be simulated for both the CRT and the optical projection displays, by intensity modulating the spot of light by a positive slope ramp function.

Target manoeuvring for advanced training can be simulated for effect, by introducing JITTER, the magnitude of which can be controlled from a front panel potentiometer control by the instructor.

4.6 MISSILE SIMULATION

Missile simulation, irrespective of the type of display used, requires generation of analogue voltages corresponding to X_M, Y_M instantaneous positions of the missile on the viewing plane. Another function Z_M is

required to be generated for the intensity modulation of the simulated missile-spot for effecting the decreasing brightness of the missile flares as it recedes away with time.

The instantaneous positions of the missile are governed by its kinematic behaviour due to the combined influence of the following:-

(a) Initial missile launch conditions.

(b) Relative missile motion due to the forward motion of the target

and (c) Guidance commands.

Each of these have been discussed analytically in detail in Chapter III, and their mathematical models in general terms are known. The subsequent sub-sections deal with the discussion of these from the point of view of their further approximation and simulation.

4.6.1 <u>Simulation for Initial Launch Conditions</u>

Before time t_o i.e. the time when the missile crosses over the LOS, the missile is under state of acceleration and roll; and the expressions (3.13) and (3.14) of Chapter III are not valid. In fact, this interval of time upto t_o is not of significance for the present simulation problem, as the missile-pilot, in any case, cannot exercise any guidance control upto this instant. Thus, precise

simulation of the missile trajectory upto time t_o is really not necessary, and approximate techniques can be used to produce the effect for the following facts:-

(a) The missile takes off from the Launcher after a certain delay (corresponding to the count-down time of the system firing sequence) after the pressing of the Firing-trigger.

(b) The missile appears in the field of view, always from below (for targets above the ground level, which is mostly the case) in the vertical plane; and from right/left in the horizontal plane depending on the direction of approach (bearing) of the target.

(c) The missile crosses the centre of the field of view at time t_o. This is an important quantitative constraint for realization.

After time t_o, the missile velocity and its attitude remain in the uniform steady state conditions, and expressions (3.13) and (3.14) become applicable. However, in the light of inferences drawn in sections 3.5.4, 3.6 and 3.7 it was noted that θ_x is a logarithmic function of flight-time multiplied by a factor $(d \sin B_s/R_o)$ whose magnitude is a function of B_s - the target bearing at the time of missile launch. The maximum variation in the magnitude of this factor is $\pm d/R_o$, which is a small

quantity ($d \ll R_o$). Also, it was noted that θ_y is a similar logarithmic function of flight-time multiplied by a factor ($2h'/R_o$), which is practically a small constant quantity ($h' \ll R_o$), independent of E_s and B_s.

Thus, with the foregoing discussion and reference to fig. 3.7 for the case study carried out in section 3.7; it can be inferred that the missile trajectory due to the initial launch conditions is essentially a problem of curve-fitting for θ_x and θ_y under the constraints specified above. The qualitative nature of curves is shown in Fig. 4.1, in which the effect of initial target elevation(discussed in next sub-section) is also depicted. θ_y is a fixed curve for a particular system specifications of h', R_o, t_o etc., whereas θ_x is a family of curves corresponding to various values of initial target bearings B_s.

Possible Techniques of Realization

The simulation of missile behaviour under its initial launch conditions, thus boils down to the problem of generating analogue functions θ_x and θ_y as shown in Fig. 4.1. The nature of the curves show striking similarity to the typical step-input response of low-pass filters, and thereby suggest a very simple and convenient method for their realization in hardware.

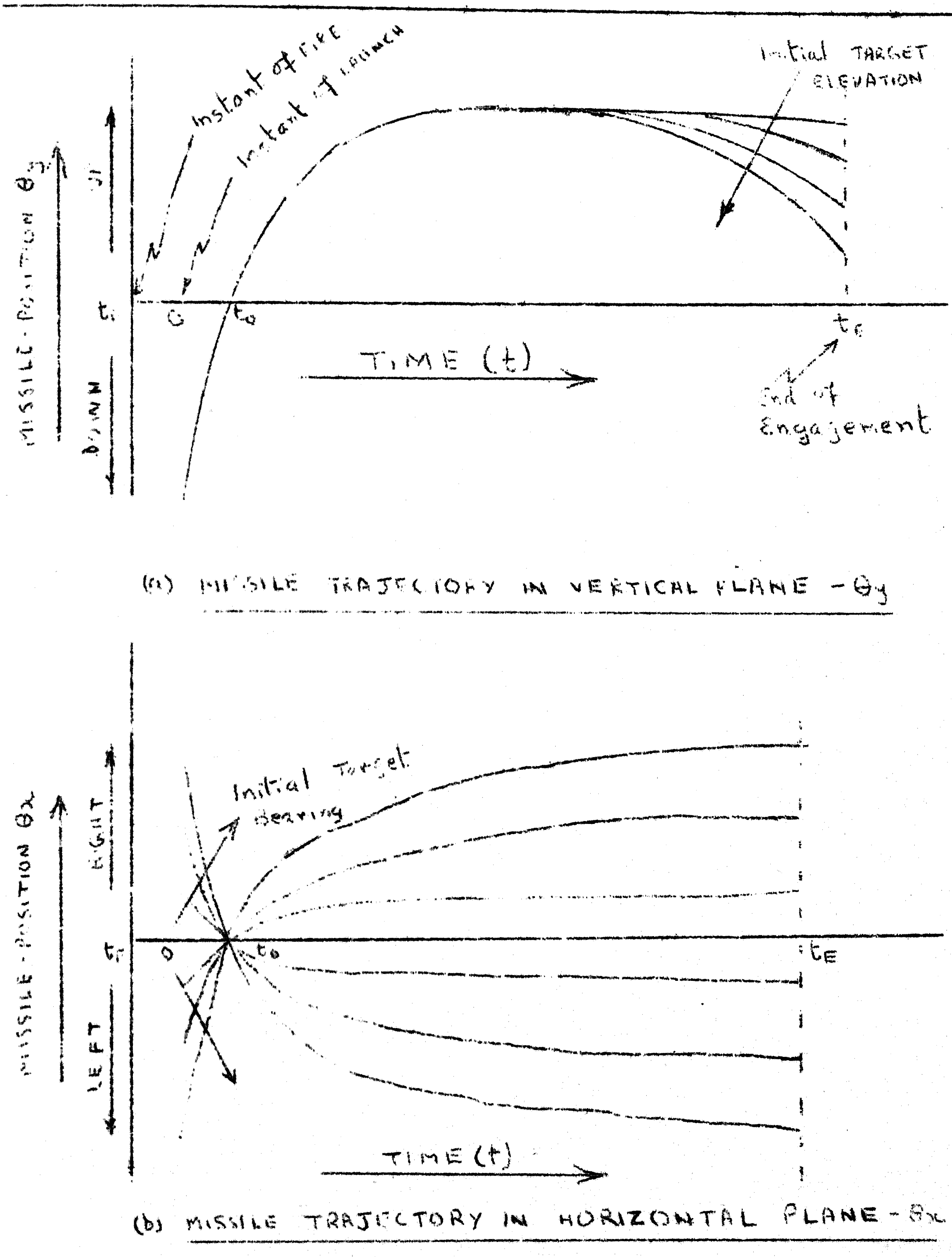


FIG. 41 MISSILE TRAJECTORIES DUE TO COMBINED INITIAL LAUNCH CONDITIONS AND RELATIVE TARGET MOVEMENT

For θ_x, the initial value is determined in magnitude and polarity by the initial target bearing setting on the corresponding front-panel potentiometer control. The delay-time, the RC time-constant and the aiming potential of the LP filter can be then so adjusted, so as to meet the constraint of time t_o and approximate the general pattern of the curve.

θ_y can be generated in a similar manner, with the difference that it has a fixed initial value and its delay-time, time-constant and aiming potential remain independent of the initial conditions.

In fact, the combined value of θ_y taking the effect of initial target elevation on relative missile motion into account (discussed in next sub-section), can be recognized as a step input response of a band-pass filter ; and can be generated by this technique by keeping the lower-cut-off frequency f_1 fixed according to the system parameters (h/R_o) and upper cut-off frequency f_2 as a dependent function of the initial target elevation setting on a potentiometer control.

4.6.2 Simulation for Relative Missile Motion due to the Target Motion

From the analysis in Chapter III, it was inferred that the relative missile motion in the vertical plane due to the targets' forward movement remains insignificant

during the early stages of engagement, but becomes the predominant factor in the later stages for a particular target speed and height above ground. From the case study of section 3.7, it was deduced that the effect of picking up the target at higher elevation implies the shifting of the curve to the left. (Refer Fig. 3.6, 3.7 and 4.1) The nature of the curve can be approximated by a parabolic curve. It is to be noted that under the stipulated constraints on the nature of the target trajectory by the system characteristics, there is little effect on missile kinematics in the horizontal plane, as discussed in section 3.6.

<u>Possible Techniques for Implementation</u>

(a) As already suggested, the combined value of θ_y due to initial launch conditions and target movement can be generated as a step-input response of a band-pass filter.

(b) Alternatively, the function can be independently generated as a

(i) step-input response of a high-pass filter;

or (ii) ramp-input response of a Low-pass filter.

In each case, the time-constant is required to be a function of the initial target elevation setting.

4.6.3 Simulation of Missile Behaviour Under Guidance

This part of simulation is most significant from the point of view of the training of the missile-pilots. The nature, the degree of precision and realism required to be incorporated for this simulation are determined by the factors already discussed in the earlier part of this chapter. The consideration of these factors had led to a 3-tier concept of the simulation models corresponding to the L, A and F-modes as indicated earlier. Thus, the simulation model, for the missile behavior under guidance are also to be considered in the light of their appropriateness for these modes.

From the study of the block-diagrams for the guidance and control loop, both in the ground-equipment as well as on the missile; the missile guidance signal path can be considered to be the F.C. followed by a single block, hereafter referred to as the transfer-function block (T.F. block). The T.F. block comprises of transfer-functions (T.F.) in cascade corresponding to:

(a) Supply frequency filter

(b) Command shaping due to Range compensation.

(c) Command shaping due to Modulus limiting.

(d) Command shaping due to Synthetic rate damping (SRD)

(e) Command link and Missile servos

(f) Aerodynamics function

(g) Missile kinematics.

The Flight-controller being the heart of the entire guidance system, is inevitably required to be duplicated or simulated for the L and A-modes; whereas in the F-mode, the F.C. of the ground-equipment itself can be used. Similar inferences can be drawn for the supply frequency filter also, as it is functionally associated with F.C.

The T.F. for the Command link and Missile servos as given by expression 3.31 is required to be simulated for all the three modes. The simulation modelling for the remaining functions of the T.F. block is to be considered with regard to their inter-relationships, which as will be observed subsequently, will lead to some interesting and significant deductions and thereby simplify the simulation models.

Definite functional relations exist between command shaping for range compensation and missile-kinematics; range compensation and modulus limiting; and S.R.D. and the aerodynamic function. These are being discussed below, followed by a summary of the deduced alternative model possibilities and their possible realization techniques.

4.6.3.1 Range Compensation and Missile Kinematics

In Chapter II, it was seen that the command signal was required to be 'shaped' for range compensation because of the inherent nature of the missile kinematics when projected on to a 2-dimensional viewing plane. If ideal range compensation is provided in the ground-equipment then the time dependent lagging characteristic of the missile kinematics would be completely neutralized. In other words, analytically the transfer-functions for range compensation and the missile-kinematics will cancel off; and the simulation model can do away with both the transfer functions for the range-compensation as well as the kinematics function. Unfortunately, as mentioned in Chapter III, complete compensation is never possible because of hardware limitations, and a small uncompensated element is always present, which from the case study of an actual system, was found to be again time dependent.

In view of the above, the following strategies could be adopted for the simulation model:

(a) For use in conjunction with the ground-equipment such as in the F-mode, the complete kinematic T.F. as given by eqn. (3.19) is required to be simulated, as the range compensation is inherent in the ground-equipment .

(b) With Synthetic targets for advanced training (A-mode), either

(i) Both transfer-functions corresponding to the Range compensation (as determined by the actual hardware used in the ground equipment) and the Kinematics function (3.19) can be simulated;

or (ii) A function corresponding to the uncompensated kinematic function (determined analytically or by computer simulation) can be generated. Alternative (b) (ii) is desirable if the simulation model is to be made exclusively for A-mode operation. However, for a universal type of simulation, approach (b) (i) is to be preferred on grounds of hardware economy.

(c) An approximate simulation, such as suitable for L-mode, can be effected by eliminating the range compensation and allowing a small fixed delay corresponding to the uncompensated kinematic function.

4.6.3.2 <u>Range Compensation and Modulus Limiting</u>

From the block diagram in Fig. 2.5, it is seen that Modulus-limiting is done after shaping the signal for range-compensation. It is observed that, but for the shaping for range-compensation, modulus limiting could

have been functionally achieved in a more convenient and simple manner at the F.C. level itself. The guidance signals during range compensation suffer time varying non-linear gains ,and thereby necessitate modulus-limiting to be resorted to after this stage.

Thus, if the simulation model eléminates the range compensation T.F. as per discussion earlier (in L-mode), the modulus-limiting block can also be eliminated, provided the simulated F.C. is designed in a manner to cater for modulus-limiting. In A-mode, the modulus-limiting is required to be incorporated after range compensation block. In F-mode, the actual hardware of the ground-equipment itself can be used.

4.6.3.3 S.R.D. and Aerodynamic Function

The co-relation between SRD and aerodynamic function has been established in the previous chapter itself under section 3.14; and Eqn. (3.34) was deduced as the combined T.F. for both.

The combined T.F. of (3.34) is convenient for simulation for all three modes, including the F-mode. Although, the SRD hardware of the ground-equipment itself can be and should be used in F-mode; but for a universal type of model, it will lead to the requirement of a separate aerodynamics block and hence will result in avoidable

circuit duplication and complexity. For a model, exclusively for F-mode, the ground-equipment SRD can be used and aerodynamic function can then be simulated corresponding to the T.F. given in expression (3.30).

4.6.3.4 Summary of Simulation-Models for Missile Guidance

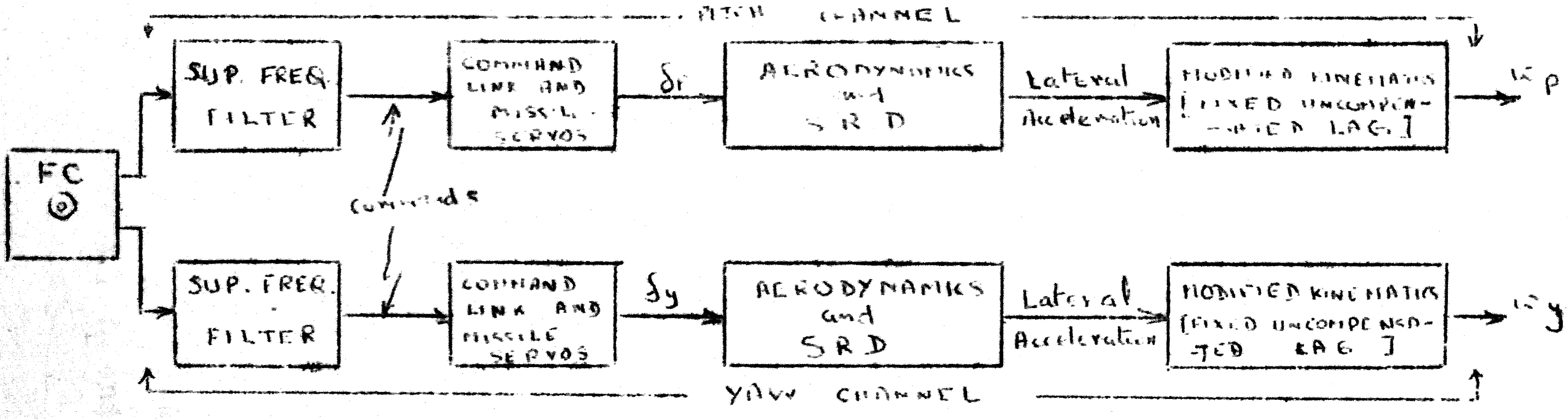
The deductions made so far in this section can best be summarized by the respective block-diagrams for each type of mode of operation as done in Fig. 4.2. It is to be noted that two identical channels are required for the pitch and the yaw planes.

4.6.3.5 Possible Realization Technique

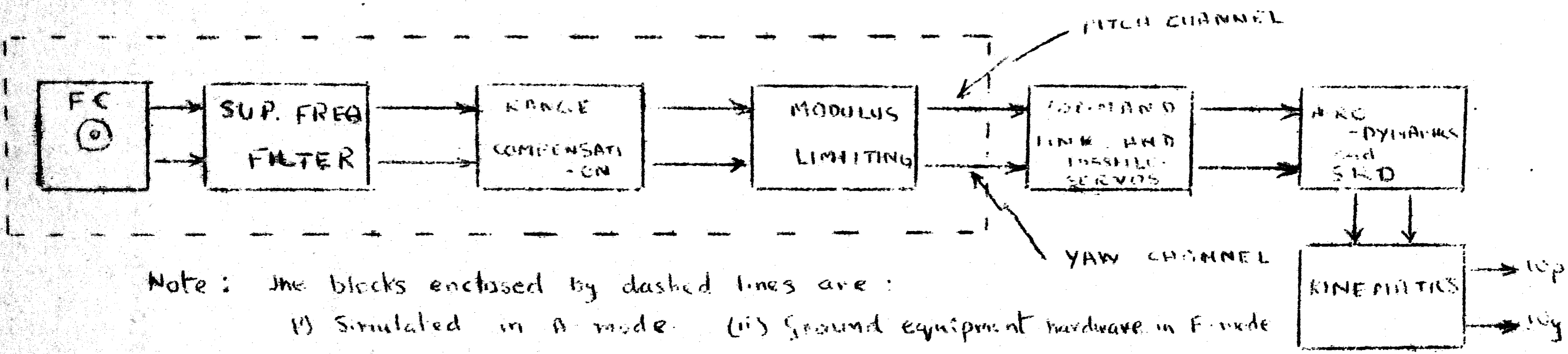
It is observed that all the blocks in the simulation models have T.Fs of the nature of quadratic filters; and therefore each one of these can be simulated by the standard design techniques for multiple-feed back, or VCVS types of filters. For standardization, it is desirable to use only one type of filters.

4.7 MISCELLANEOUS FEATURES

This section deals with a desirable feature i.e. performance evaluation of the trainees, and a necessary feature i.e. the timing and control functions associated with the simulator and display units.



(a) L-FICTE MODEL



Note : The blocks enclosed by dashed lines are :
(i) Simulated in A mode (ii) Ground equipment hardware in F mode

(b) A and F MODELS.

FIG. 4·2 SIMULATION MODELS FOR MISSILE GUIDANCE

.7.1 Performance Evaluation

Performance evaluation is a very desirable feature to be incorporated in the training device, not only for the instructor to assess the trainees; but also for the psychological satisfaction of the trainees themselves after each practice engagement. The feature should further enable both qualitative and quantitative assessments. The quantitative assessment is required as a measure of proficiency for testing, grading and maintaining records of the trainees; whereas the qualitative assessment may be adequate for routine practice.

From the case study of section 3.7, it was inferred that it is the gathering phase which is the most crucial period for guidance; and therefore emphasis is required for intensive training of missile-pilots for this phase in particular. Thus, the time taken by a trainee to 'gather' the missile is important, and further a measure of the time he keeps it 'gathered' during the engagement period is again significant. It stands to reason that an improvement in these timings will obviously, increase the probability of making a successful interception with the target.

The criterion for 'Gathering' is that

$$(X_T - X_M = 0) .\mathrm{AND}. (Y_T - Y_M = 0)$$

where X_T, Y_T and X_M , Y_M are the x-y co-ordinates

corresponding to the instantaneous positions of the target and the missile respectively.

The criterion for 'HIT'/'MISS' decision-making is that the missile must be gathered at the instant of end of engagement time, which is the expected time of interception with the target. Taking cognizance of the proximity-fuze in the missile, if 'F' be the maximum effective range of the fuze ; then the Gathering criterion at the end of engagement time is modified to the condition

$$[(X_T-X_M)^2 + (Y_T - Y_M)^2]^{\frac{1}{2}} \leq F$$

The performance evaluation feature can be practically realized in a number of alternative ways using logic gates, gated clock pulses and counters, strip- chart recordings and lamp indications etc.

4.7.2 Timing and Control Functions

From the study of the system, it is seen that a complete engagement encounter is a time-bound sequential operation. Thus, any simulation endeavour will require a timing clock to be switched on at the time of pressing the firing trigger, and reset at the end of engagement time.

Moreover, in practical hardware realization of the various functions required to be generated, certain gate pulses may be required to be produced to act as control pulses. Thus, a timing and control unit is inevitably

required to be associated with the simulator unit.

4.8 OVERALL BLOCK SIMULATION MODEL

From all the foregoing discussion in this chapter, an overall block simulation model for the intended training-aid can be deduced.

From the review of the factors considered and the deductions drawn for each one of them, the following salient facts emanate:

(a) To achieve the aim of progressive training, a 3-tier system, corresponding to the Learner, Advanced and Field levels of training is desirable.

(b) Correspondingly , three alternative simulation models are feasible; each one being appropriate to the requirements of precision, and realism for the intended level of training.

(c) Similarly, there are three feasible display systems; each one being compatible to one of the three possible simulation schemes.

Thus, there is a choice of making three independent training-aids appropriate to the three levels of training; or to have a single universal type of simulator unit, which will comprise of all three simulation models corresponding to the Learner (L), Advanced (A) and Field (F) levels of training; and any one of these models can be selected by a common 'MODE SELECTION SWITCH', and coupled to the

appropriate desired display system interface.

A decision on selection of the choice given above is a debatable issue. However, the following factors in this regard are worth noting for the simulator unit:

(a) There is a large quantum of hardware common to all the three models.

(b) The variation among the three models is small and a change-over from one model to the other can be realized by a single multiple-wafer switch.

Thus, there is a possibility of combining all the three models into one universal type model with the additional advantages of achieving standardization of equipment and flexibility of application, without incurring any significant complexity to the equipment or addition to the cost.

The universal type of model is, therefore, recommended for ultimate development and adoption into service. A schematic block diagram of such a model is given in Fig. 4.3. The switching required for selection of mode L, A or F ; corresponding to the Learner, Advanced or Field levels of training, has been included to emphasise the simplicity of the operation.

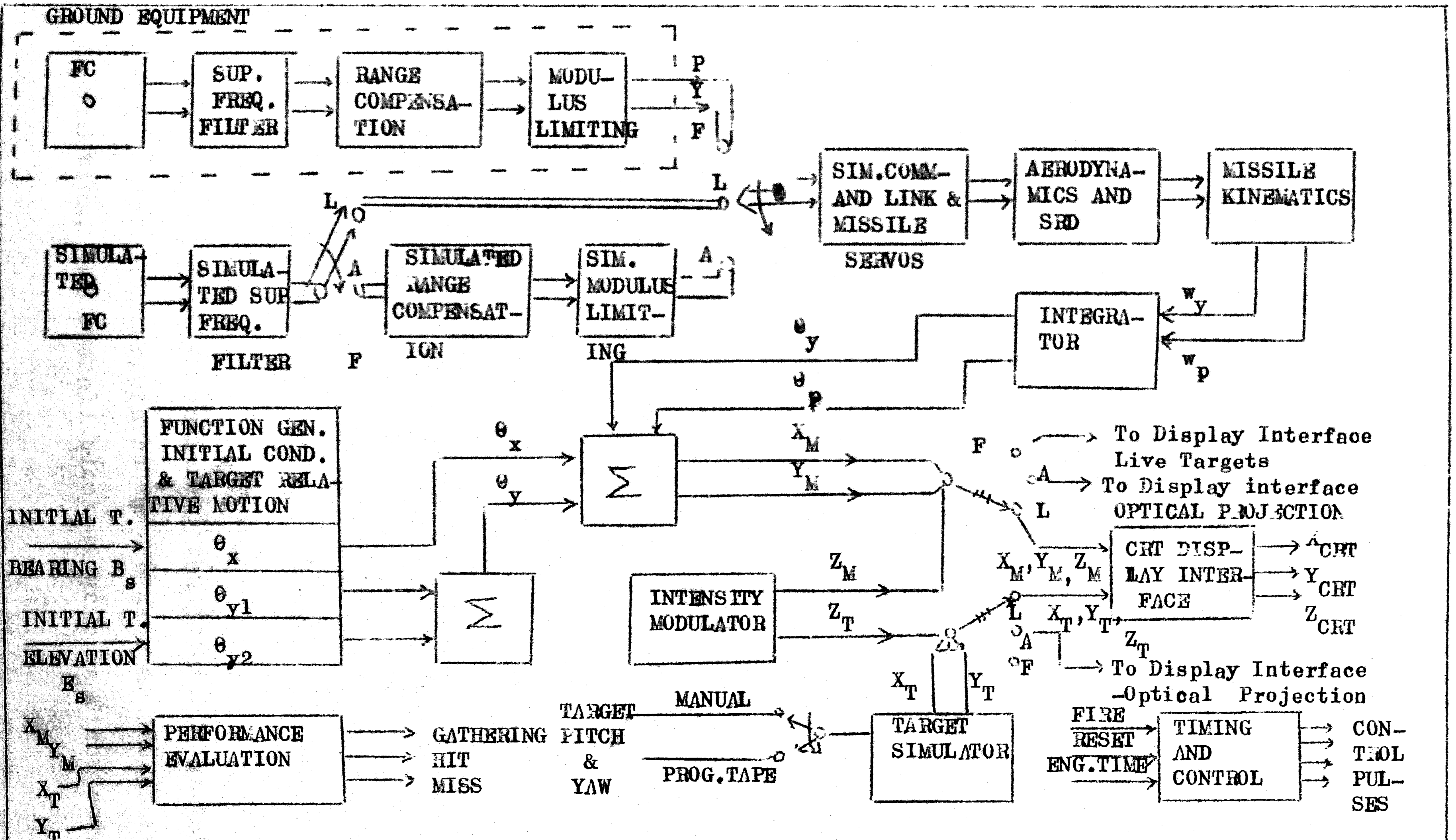


FIG. 4.3 SCHEMATIC BLOCK DIAGRAM FOR PROPOSED UNIVERSAL TYPE COMMAND GUIDANCE SIMULATOR

CHAPTER V

DESIGN AND HARDWARE REALIZATION

To check and establish the credibility and the feasibility of the simulation model developed in the last chapter, a laboratory model corresponding to the L-mode of the proposed simulation model has been successfully designed and fabricated; along with a Flight-controller, compatible with the original flight-controller of an existing system.

This chapter deals with the design and the hardware implementation of the F.C. and the Command Guidance Simulator. Conventional operational Amplifier Circuitry has been used throughout the system, for which standard design techniques exist; and therefore, no endeavour has been made to include any design derivations or calculations.

For the simulator design, a few system parameters are required to be assumed/known. These parameters have been adopted from a typical existing system, and are given in Appendix 'C'.

After briefly mentioning the general qualitative considerations incorporated in the general design and fabrication, the overall block-diagram is discussed, followed

by the design considerations and brief circuit description of each constituent block.

5.1 CONSIDERATIONS FOR DESIGN AND FABRICATION

The following general considerations have been kept in mind as the guiding factors for the design and fabrication:-

(a) Standardization of circuits and components, with an aim towards simplicity of equipment and reduction of the subsequent inventory of spares required for maintenance.

(b) Built-in reliability by selection of suitable devices, components and application of conservative design techniques.

(c) Convenient maintenance e.g. accessibility and location of vital components like trim-pots etc; aids for quick fault-diagnosis, facility for in-circuit testing of sub-units.

(d) Ease and simplicity of operation for the users and incorporation of fail-safe systems.

(e) Cost of the equipment commensurate with the requirements of reliability and functional requirements.

Considerations for the reduction in weight and size have not been given much attention for the development of

the laboratory model. These can be taken care of, without compromising the other considerations, during the prototype development stage.

5.2 SYSTEM BLOCK DIAGRAM

The complete training-aid as developed consists of three units:-

(a) Flight-controller

(b) Command Guidance Simulator

and (c) CRO for display.

A 2-channel strip-chart recorder is optional for recording the performance of trainees.

The Flight-Controller is a device designed and fabricated such that it is functionally compatible to the original device, (used with the actual system simulated), using an entirely different principle.

The Command Guidance Simulator is essentially the hardware implementation of the L-mode operation of the overall universal type of simulation-model, developed and recommended for ultimate adoption into service, in the last chapter. The display interface required for CRT display has been incorporated within the simulator unit for convenience.

Fig. 5.1 shows the block diagram of the Command Guidance Simulator; which has been fabricated, using

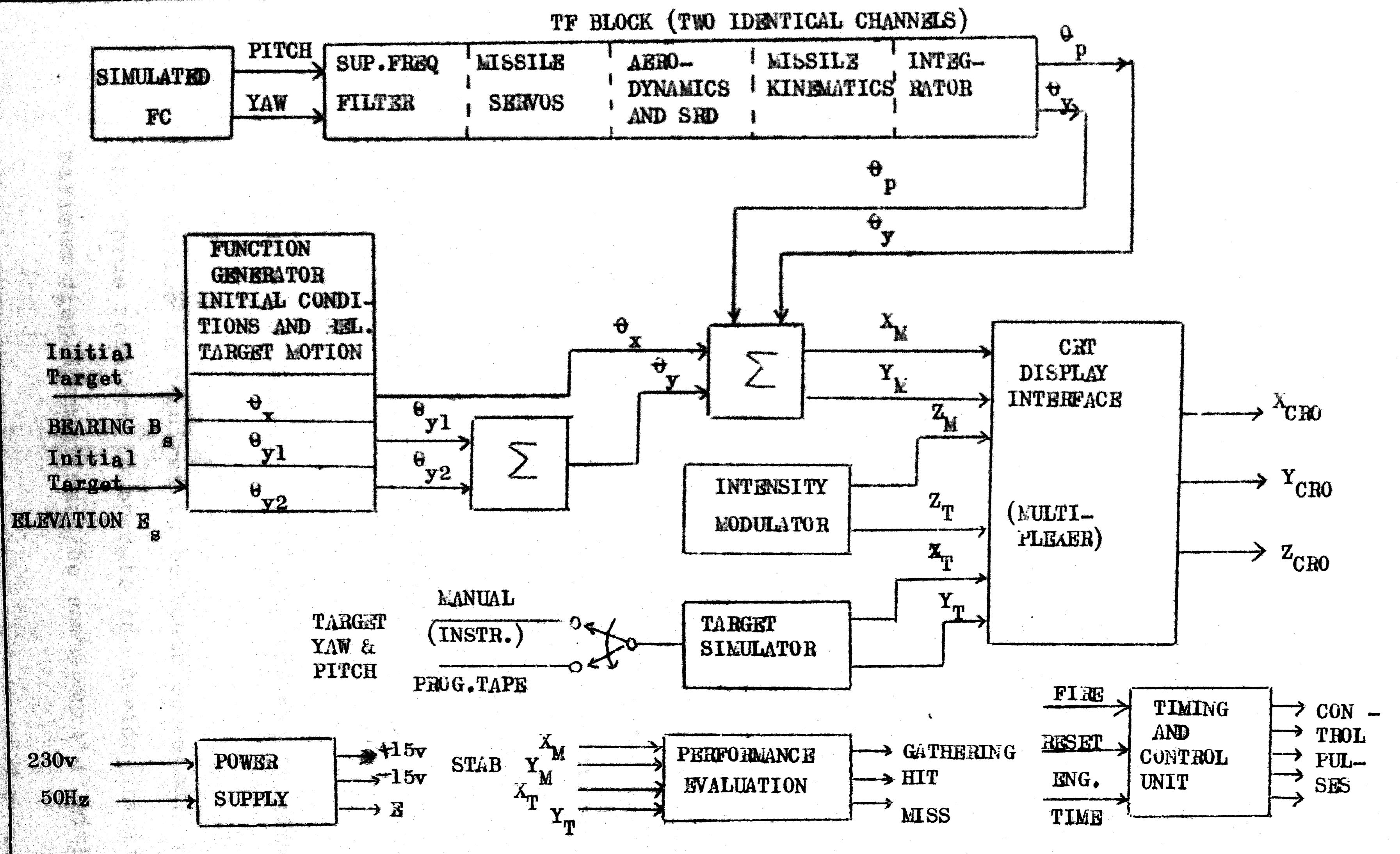


FIG. 5.1 BLOCK DIAGRAM—COMMAND GUIDANCE SIMULATOR (FABRICATED)

printed circuits. The block diagram can be sub-divided into the following sub-units:-

(a) Flight-Controller

(b) T F block

(c) Function generator for initial conditions and relative target movement

(d) Target simulator

(e) Intensity modulator

(f) CRT Display interface

(g) Performance evaluation

(h) Timing and control

(i) Power supply.

Each of these sub-units is briefly described below. Timing and control unit is discussed immediately after the FC, as it is linked with all other units. The circuit diagrams shown are mostly as per the actual printed circuit layouts.

5.3 FLIGHT-CONTROLLER

Design Criterion

The design criterion for simulating the original FC were:-

(a) The device is required to be thumb operated. Hence the force required to operate the device and its maximum displacement must be commensurate with

normal thumb movements i.e. the force required must be less than 1/4 lb. and maximum deflection restricted to to $\pm \frac{1}{2}$ inch.

(b) The outputs are required as bipolar DC voltages, in two independent channels for the pitch and the yaw movements. The maximum output corresponding to the maximum displacement of the transducer is required to be calibrated to $\pm$ 10 v for compatibility with the original FC (used with actual system.)

(c) It is desirable to have 400 Hz. ripple and its harmonics in the output for realistic simulation.

Principle used

With the above constraints a FC has been designed based on electrical strain gauges connected in a bridge The incremental change δR in resistance of a strain-gauge due to a strain ε is given by*

$$\delta R = R_g \cdot \varepsilon \cdot S_G \qquad (5.1)$$

where R_G is the gauge resistance for $\varepsilon = 0$ and S_G is a GAUGE-FACTOR determined by the nature of the material.

For small values of strain (less than 5 %),the bridge imbalance output voltage δE is given by

$$\delta E = 2\ I_g \cdot R_g \cdot S_g \cdot \varepsilon \qquad (5.2)$$

where I_g is the gauge-current.

*''EXPERIMENTAL STRESS ANALYSIS'' by James W.Dally and Riley

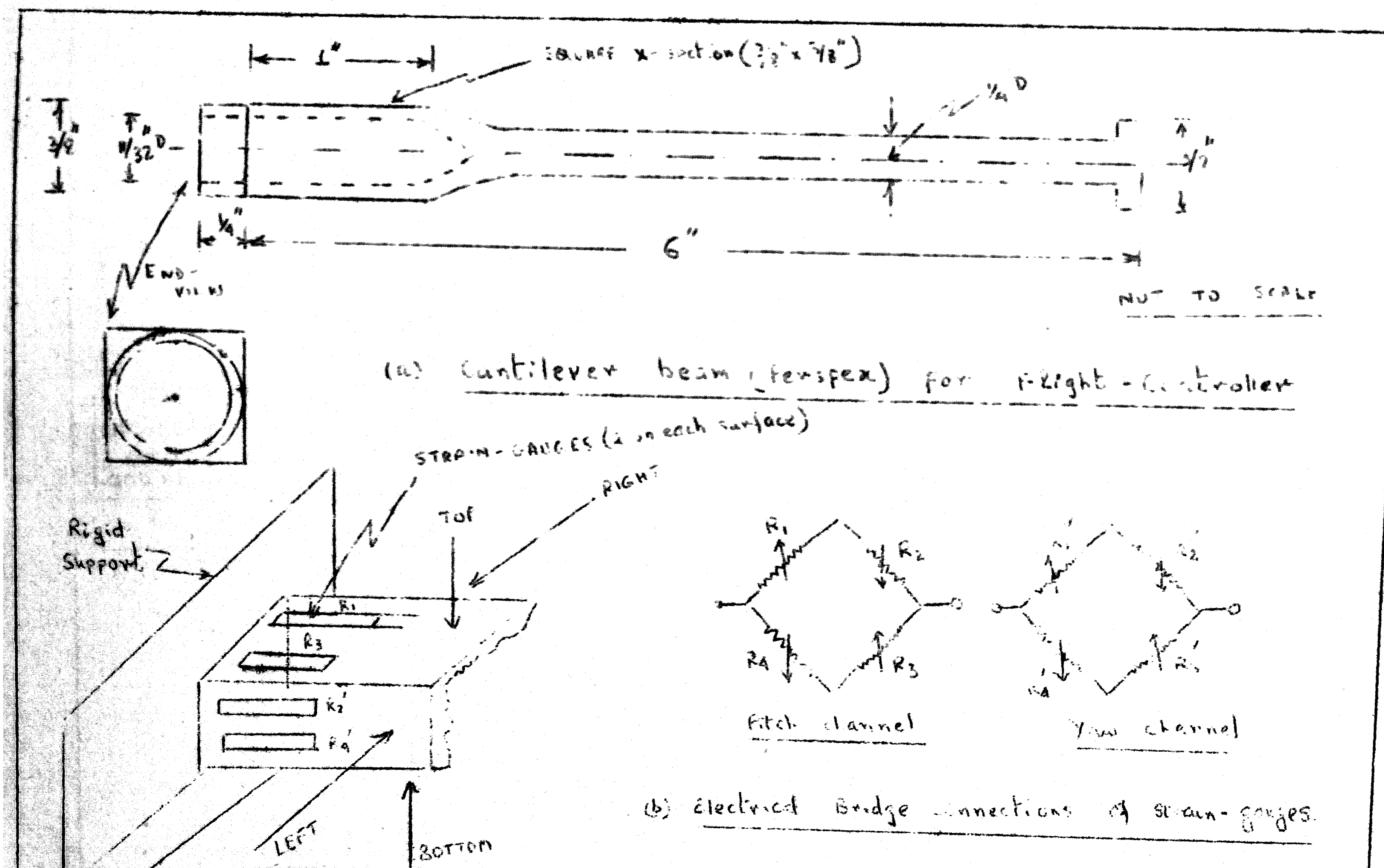
Realization

A cantilever beam machined from a perspex rod, as shown in Fig. 5.2 was designed such that the design constraints for the mechanical part of the transducer were satisfied. The strain-gauges have been mounted in pairs on each surface of the square cross-section. The gauges on opposite faces have been connected to form two independent bridges corresponding to the pitch and yaw displacements. This arrangement enables:-

(a) Automatic temperature compensation

(b) Cancellation of the cross-coupling effect in the two planes.

The bridges are excited by a 400 Hz Wien-bridge oscillator, and have facility for null-balance adjustment under zero displacement/strain condition. The imbalance voltages produced by the displacement of the cantilever rod in the two planes are amplified, and filtered for noise by a NIC filter in two identical channels corresponding to the pitch and yaw outputs. Phase-sensitive-detectors convert these amplified ac voltages into proportional bipolar DC voltages, which are then averaged out in corresponding integrator circuits. The NIC filters can be tuned to the excitation frequency and the gains of the integrators can be adjusted for calibrating the output by means of conveniently located



(a) Cantilever beam (perspex) for flight-controller

(b) electrical Bridge connections of strain-gauges.

FIG. 5.2. FC MECHANICAL DESIGN AND BRIDGE CONNECTIONS

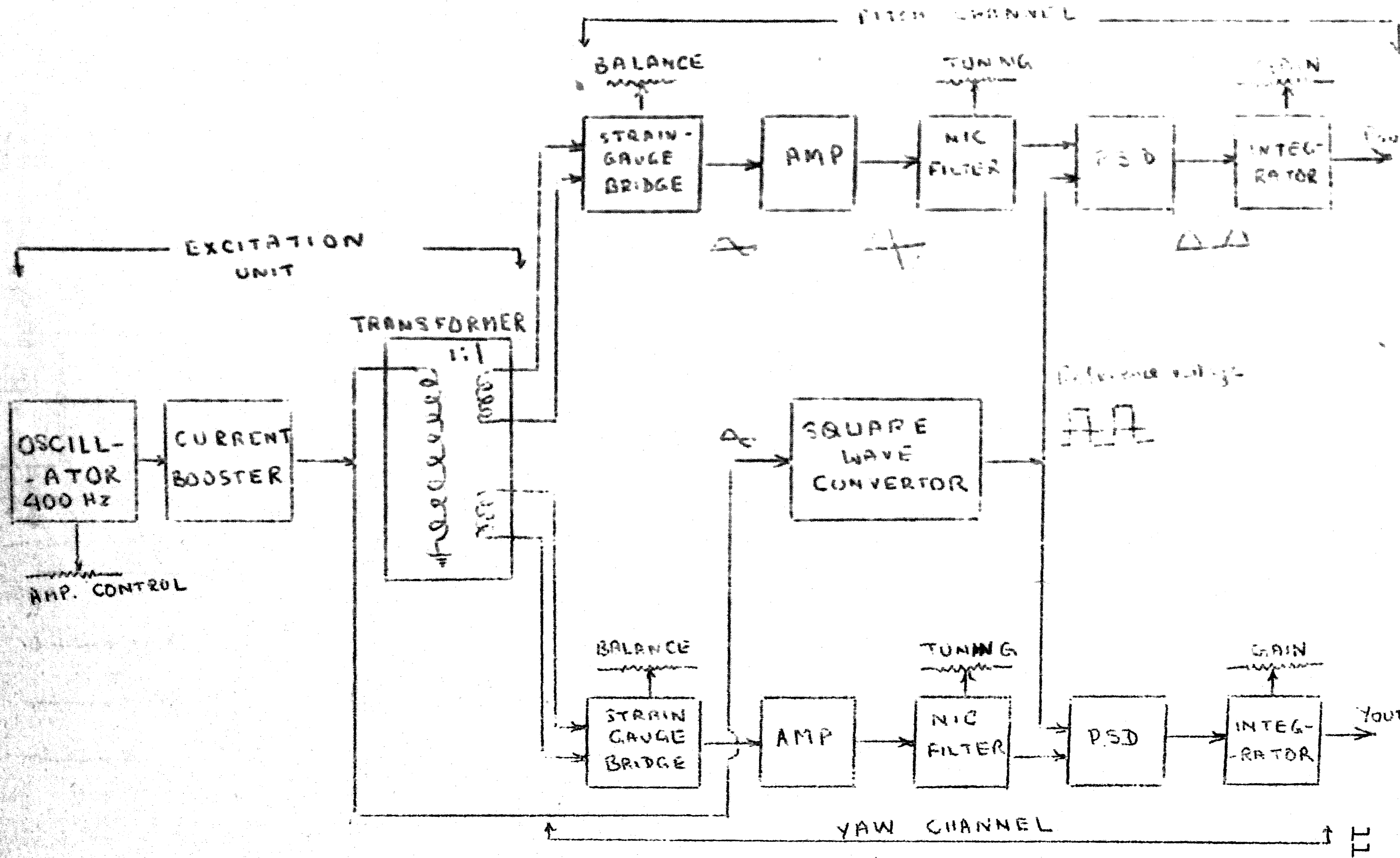


FIG. 5.3 BLOK DIAGRAM — FC ELECTRONICS

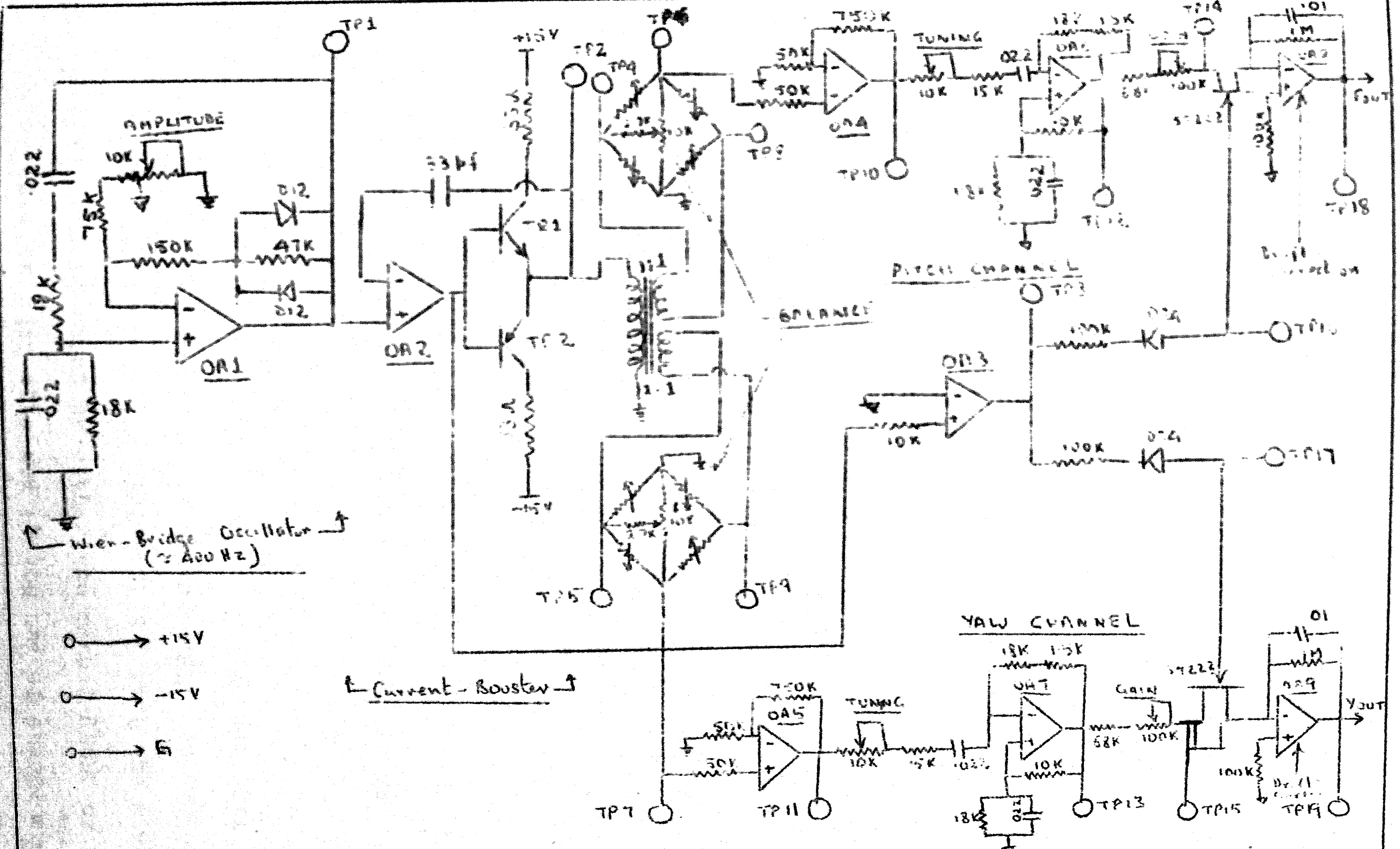


FIG 5.4 CIRCUIT DIAGRAM — FC ELECTRONICS

trimpots. Fig. 5.3 gives the block diagram and Fig. 5.4 shows the electronic circuitory used.

The feature of Modulus-limiting at the FC has been incorporated mechanically by means of an adjustable circular aperture on the front cover plate of the FC, which limits the maximum allowable displacements of the cantilever rod.

5.4 TIMING AND CONTROL UNIT

It has been designed to meet the requirements of the system time-bound characteristics and other control functions in the simulator unit.

The control pulses generated are illustrated in Fig. 5.5, and are generated by Latches. To achieve standardization of components and to minimize requirements of different voltages from the power supply, TTL technology has been deliberately avoided. All the requisite latches are designed using operational-amplifiers (OA) . An analogue timing clock is generated by a linear ramp function, which is sampled by various OA comparators to generate the various timing events.

The circuitry used is shown in Fig. 5.6. OA1 is the FIRED LATCH which is set by the FIRE button on the simulator unit or by the REMOTE FIRE (with the missile-pilot), and is reset by either the manual RESET or the auto-reset trigger obtained at the end of engagement time;

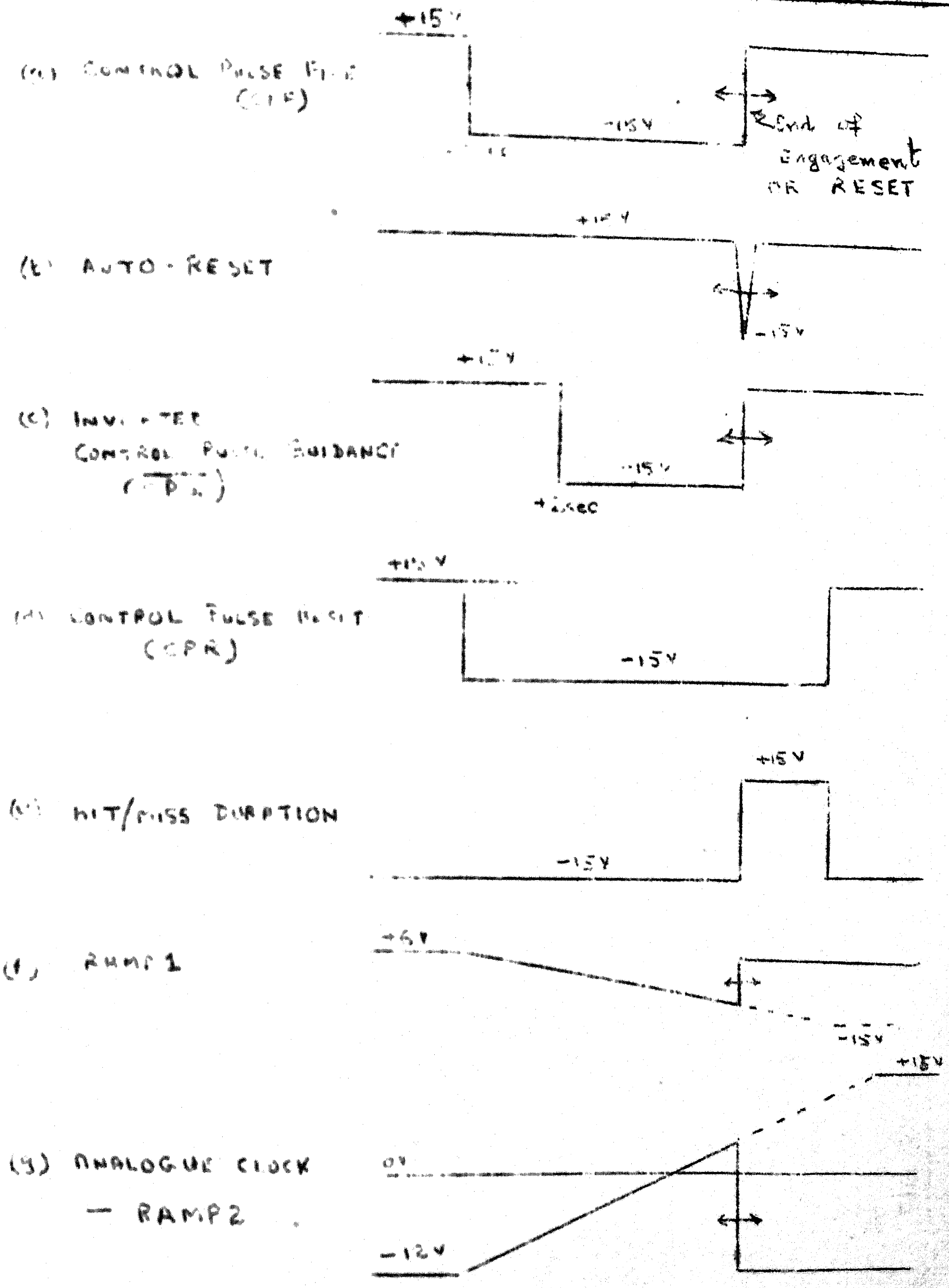


FIG 5.5 WAVEFORMS – TIMING AND CONTROL UNIT

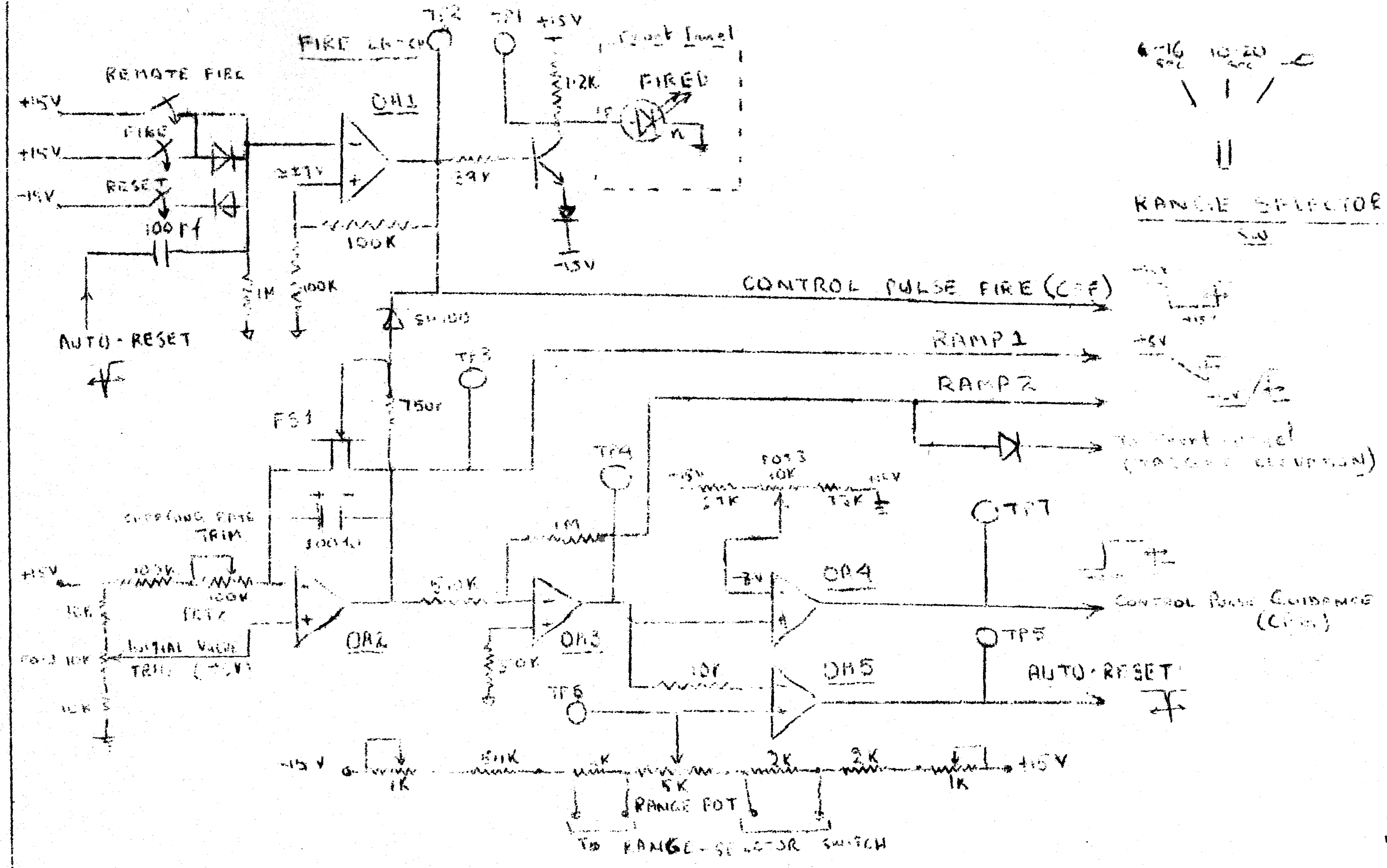


FIG 5.6. TIMING AND CONTROL UNIT

and thus generates 'Control Pulse Fire' (CPF). TR1 is a transistor invertor which controls the FIRED indication (LED) on the front panel. OA2 produces a linear ramp (RAMP1) for the duration of CPF. It is preset to commence ramp at + 6v (at the instant of FIRE) at the rate of ½ volt/sec. A FET switch, with CPF applied at its gate, controls the beginning and reset timing of the ramp.

OA3 gives a gain of 2 to RAMP1 to obtain the analogue clock RAMP2, which commences from -12v level at the rate of 1 volt/sec. OA4 and OA5 are two open-loop comparators, which compare the timing ramp with preset voltages to generate Control Pulse Guidance (CPG) and end of engagement/AUTO-RESET trigger . POT3 for OA4 is pre-set for a voltage corresponding to the system characteristic time t_o (2 secs. in this case), when the guidance is enabled. The range-pot on the front-panel gives the reference voltage for OA4. The target speed and the initial range of the target in terms of the engagement time are preset on the range-pot in three switchable continuously variable ranges of 6-16 sec., 10-20 sec. and INFINITE, through a chain of resistances, as shown in the diagram.

OA22 (refer Fig. 5.10) is a RESET-LATCH controlled by the FIRE and RESET press-buttons on the front panel,

and produces control Pulse Reset (CPR), which controls the READY indication (LED) on the front-panel. It has been located in the 'Performance Evaluation' printed circuit card because of fabrication convenience. $\overline{CPG}$ is obtained on the same card by a transistor invertor TR6.

5.5 T.F BLOCK

Two identical cards have been made for the pitch and the yaw channels. The circuit diagram for one channel is shown in Fig. 5.7. The input from the Flight-Controller to the TF block is enabled only at time t_0 (+ 2sec. in this case) by the opening of the FET switching gate by $\overline{CPG}$ as shown in the diagram.

The supply frequency filter is a low pass VCVS filter; whereas the remaining filters corresponding to the transfer-functions for the Missile-Servos, Aerodynamics and SRD and the Kinematics are multiple-feed back type of OA filters in tandem. The last stage of the TF block is an integrator which produces the analogue angular position θ_p/θ_y of the missile due to guidance commands.

5.6 FUNCTION GENERATOR-INITIAL CONDITIONS AND RELATIVE TARGET MOVEMENT

Based on the discussion under the same heading in the previous chapter for the simulation modelling, the missile kinematics for the initial conditions is achieved as

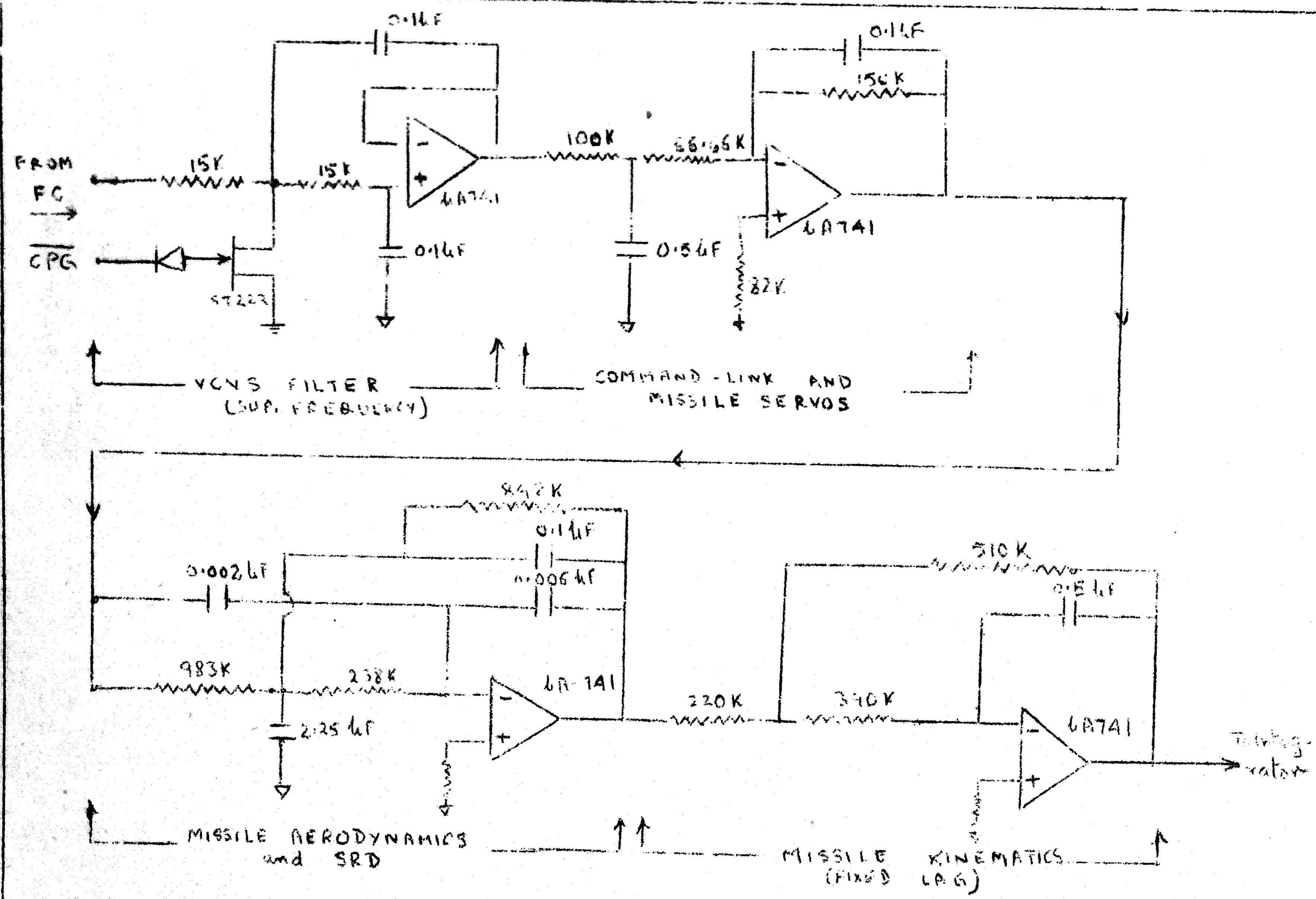


FIG 5.7 CIRCUIT DIAGRAM — TF BLOCK (Only one channel shown)

step-input responses of first order low-pass RC filters.

Referring to Fig. 5.8, the capacitor C_1 remains charged to a voltage (with reversed polarity) determined by the pot-setting of the TARGET BEARING on the front-panel, through invertor OA8 and FET switch FS4. On 'FIRING', the capacitor charges exponentially towards the voltage level determined by the T.BEARING pot . The rate of charging is adjusted by POT4 such that the output (θ_x) monitored at TP10 is 0 v at time $t_o = 2$sec. θ_x thus generated is added to the yaw channel output of the TF block in OA9 to obtain X_M co-ordinate of the missile.

Similarly, θ_{y1} is generated by capacitor C_2 which normally remains charged to a fixed voltage (+ 15v)* and on 'FIRING' begins to discharge towards -15v at a rate determined by POT5, which is adjusted to give a rate commensurate with the system requirements, as discussed in Chapters III and IV. (Refer Fig. 4.1).

The effect of the relative target movement is simulated by a ramp -input response of a low-pass RC filter as suggested in Chapter IV. RAMP2 (referring to Fig. 5.8 again) is clipped at 0 v. level by diode D_1, to obtain a delay of 10 secs., and is applied to capacitor C_3, which normally remains discharged by switch FS7.

* This ensures that the missile position on display remains at -15v and thus it is out of the view, when the system is not in FIRED state.

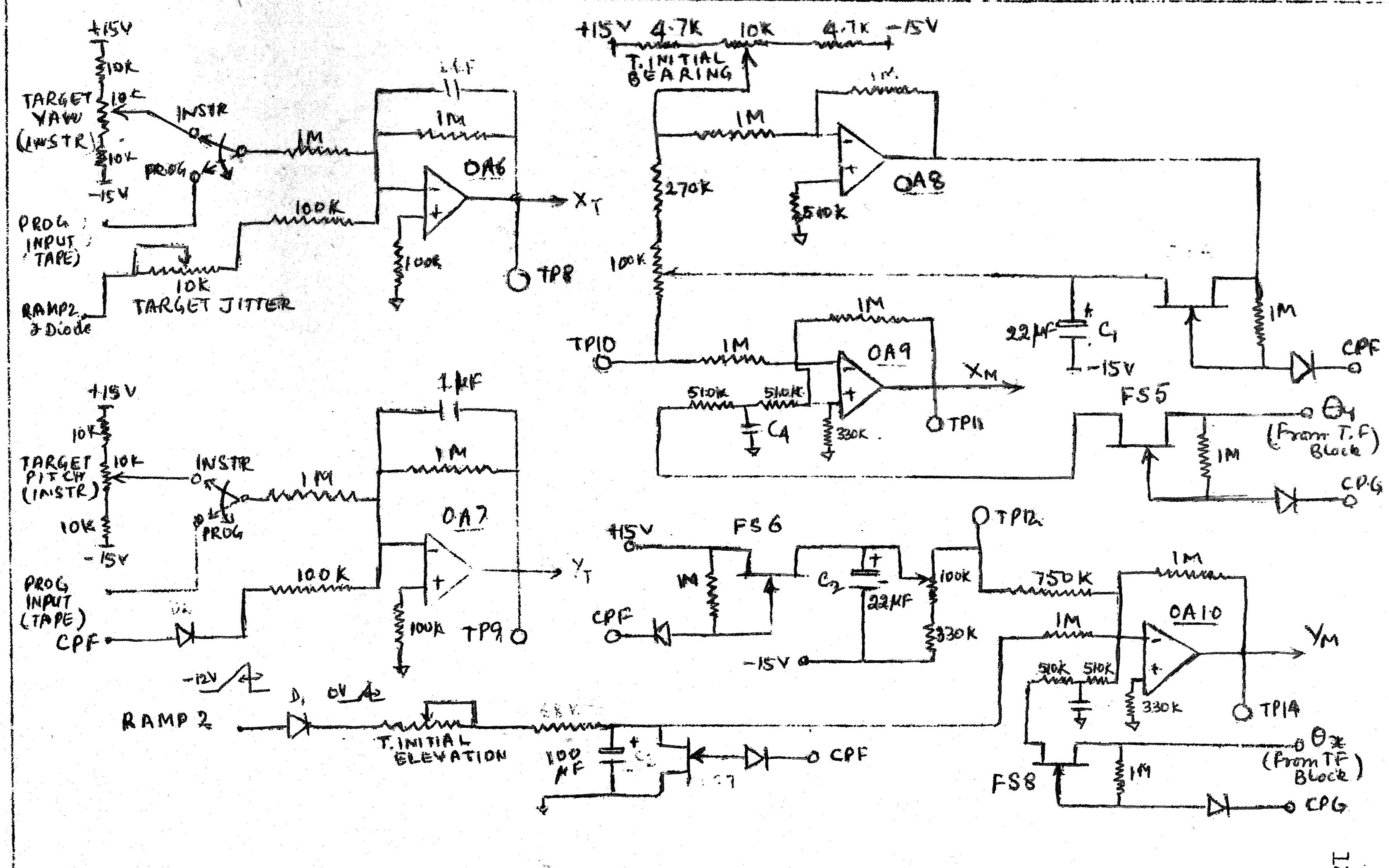


FIG. 59 FUNCTION GENERATOR UNIT

The time-constant of the filter is determined by the TARGET ELEVATION setting on the front-panel. The output of capacitor C_3 i.e. θ_{y2} is summed up with θ_{y1} and the pitch output of the guidance TF block, to obtain co-ordinate Y_M of the missile.

The guidance TF outputs, in both pitch and yaw channels, are connected only at time t_o through switches FS8 and FS5 respectively. Capacitors C_4 and C_5 suppress switching spikes.

5.7 TARGET SIMULATOR

As per the discussion in Chapter IV, the target initial conditions, have already been incorporated as front-panel controls for the missile simulation, as mentioned in previous section.

For the target trajectory under dynamic conditions, facility for both programmed tape input and Instructor's pot control has been incorporated. Either of these can be selected by a front-panel toggle switch, as shown in Fig. 5.8.

OA6 sums up and smoothens out the dynamic target position along X-axis (of viewing plane) and a jitter obtained from a slow-frequency astable ($\simeq$ 3 Hz) in the Intensity-modulator unit (the magnitude of which is controllable from a front-panel pot-JITTER control). The output of OA6 is X_T, the x-co-ordinate of the target position.

Similarly, the y-co-ordinate Y_T is produced by OA7 by summing and smoothening the dynamic target position along the y-axis. The other input to OA7 is CPF applied through D_2 to ensure that the target position is normally at -15v when not in fired state, and hence it is out of the view on the display.

5.8 INTENSITY MODULATOR

Referring to Fig. 5.9, the desired Z_M and Z_T functions, as discussed under the simulation modelling, are generated by OA13 and OA14 respectively. For Z_M, the positive going RAMP2 is added to the output of OA11, which is a slow $\simeq$ 3Hz astable multivibrator, to produce the effect of missile blinking. Z_T is produced basically from the negative going RAMP1. The respective multiplexing Gate Control Pulses (discussed under display) are added to both Z_M and Z_T to produce the blanking effect during the fly-back period on CRT display. CPF is also applied to both Z_M and Z_T to ensure reduced intensity level, when the system is not in fired state.

5.9 CRT DISPLAY INTERFACE

A single beam CRO is used, with equal gains (2 volts/cm) on both x-y channels. As mentioned in previous chapter under CRT display techniques; the generated missile position outputs X_M, Y_M and Z_M are multiplexed with the corresponding

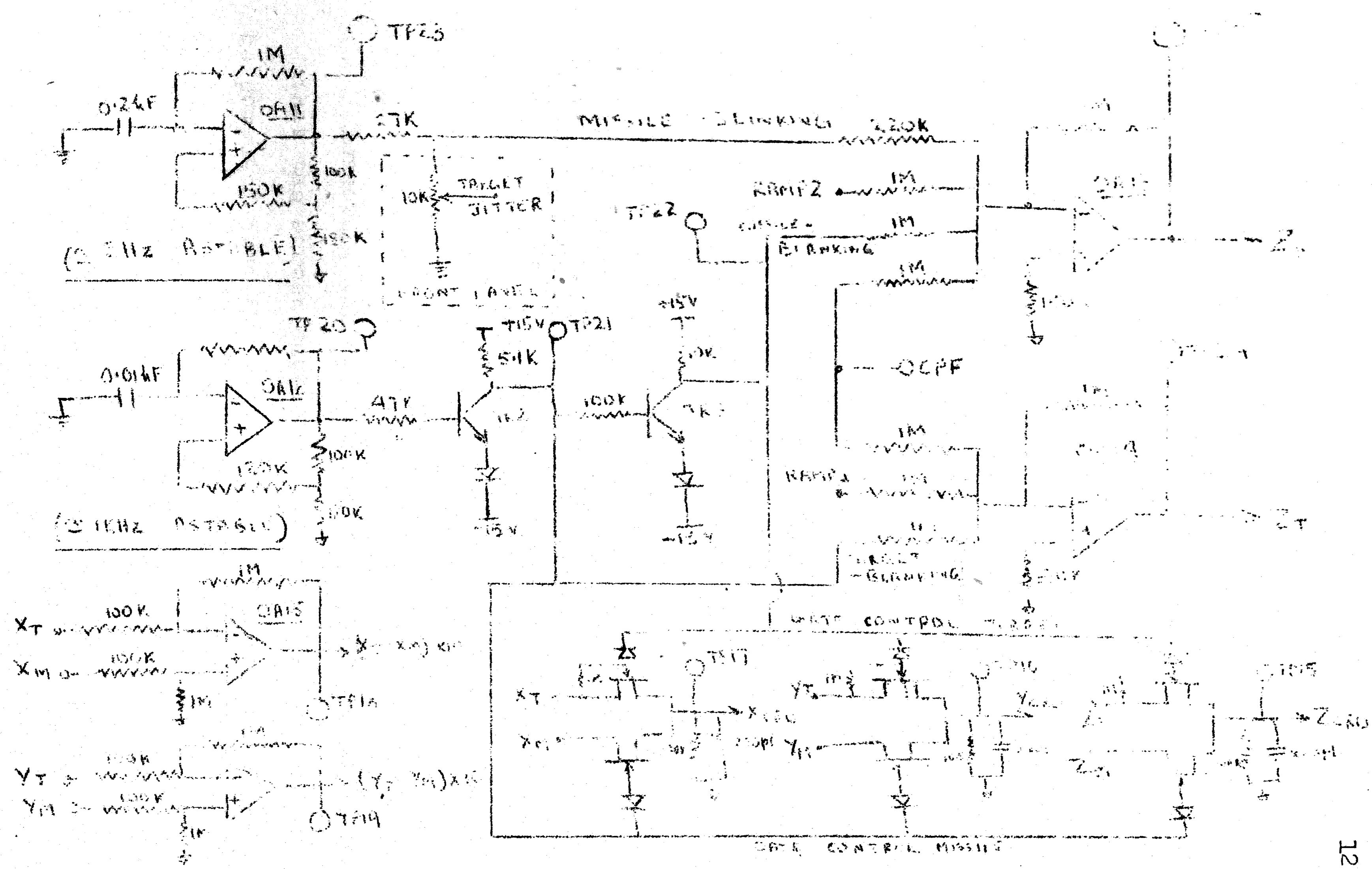


FIG. 59. INTENSITY MODULATOR AND CRT DISPLAY INTERFACE

generated target positions X_T, Y_T and Z_T respectively in three SPDT type of FET switches, to produce X_{CRO}, Y_{CRO} and Z_{CRO} as shown in Fig. 5.9. The respective complimentary Gate Control Pulses for the missile and the target co-ordinates are produced by two transistor invertors TR2 and TR3 from an OA astable multivibrator OA12 ($\simeq$1KHz).

The CRO screen represents the field of view (viewing-plane) of the missile-pilot. The scaling of the screen is done as follows:-

The maximum output voltage of the Simulator unit during guidance being 8v and the normal vertical space of CRO screens being 4 cm., the voltage scale is 2v/cm. Further, the normal field of view being 15°, the angular scale is 1.875°/cm. or 0.033 radian/cm. Thus, the CRO screen scaling can be stated as

1 Division = 1 cm = 2v = 1.875° = 0.0333 radian

Moreover, the distance of the trainee from the CRO such that the screen subtends an angle of 15° at the eye, can be computed from the above to be about 32 cms.

5.10 PERFORMANCE EVALUATION

Quantitative performance evaluation of trainees can be done by recording the instantaneous positional errors $(X_T - X_M)$ and $(Y_T - Y_M)$ during a practice engagement on a

2-channel strip-chart recorder. The difference amplifiers OA15 and OA16 (Fig. 5.9) produce these error voltages with a gain of 10.

Approximate qualitative assessment facility is incorporated by means of lamp indications (LEDs). The error voltages generated are compared in four open-loop window-comparators OA17 to OA20 (refer Fig. 5.10) with voltages corresponding to the permissible error window (due to the proximity fuze in the missile). The permissible error voltages can be preset on POTS 6 and 7 . When all the four comparator outputs are high (implying that the error is between the permissible error-window) and the system is in fired state with $t > t_0$ (CPG high), transistor TR4 goes low (negative logic NAND) and invertor TR5 switches the GATHERING indication on. The coincidence of the 'gathering' condition with the end of engagement is sensed in a diode sampling gate, which produces a positive trigger which through TR7 sets the HIT LATCH OA21 high, and HIT indication is lighted. In this state , the collector of TR8 being high, the MISS indication is off. The HIT Latch is reset by the trailing edge of the CPR on pressing of the RESET button. In case, a HIT has not been sensed at the end of engagement period, TR8 switches the MISS indication on. TR9 inhibits conduction of TR8 till end of engagement (CPF duration).

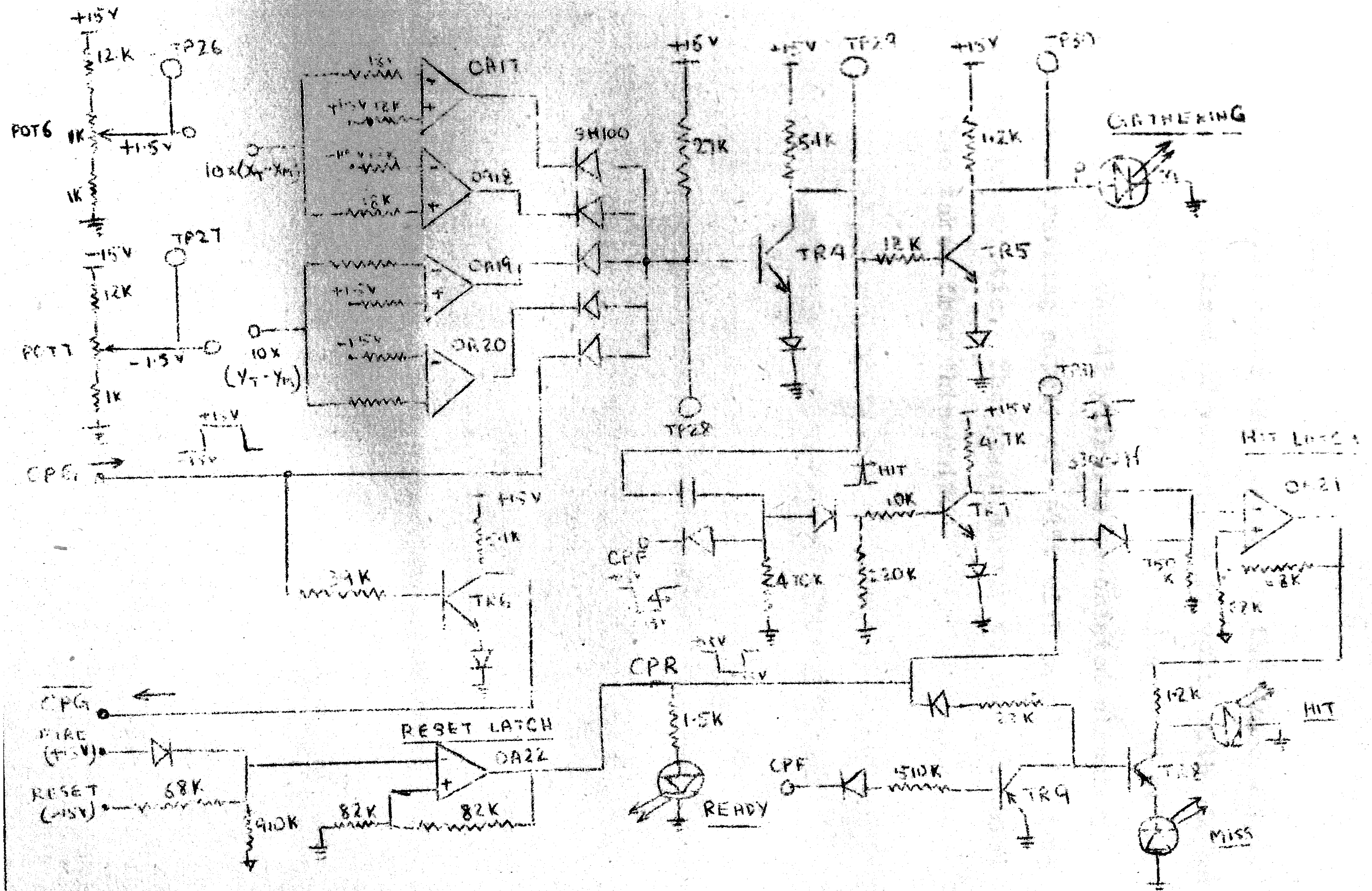


FIG. 5.10 PERFORMANCE EVALUATION

5.11 POWER SUPPLY

Fig. 5.11 shows the layout for the power-supply unit. Two stabilized DC voltages $\pm$ 15 volts with 500 mA rating are produced. A 723 chip produces + 15 volts stabilized and a μA 741 with its associated circuitry produces a tracking supply of -15v with overload fold-back characteristic. The power supply to the simulated FC is also taken from this unit.

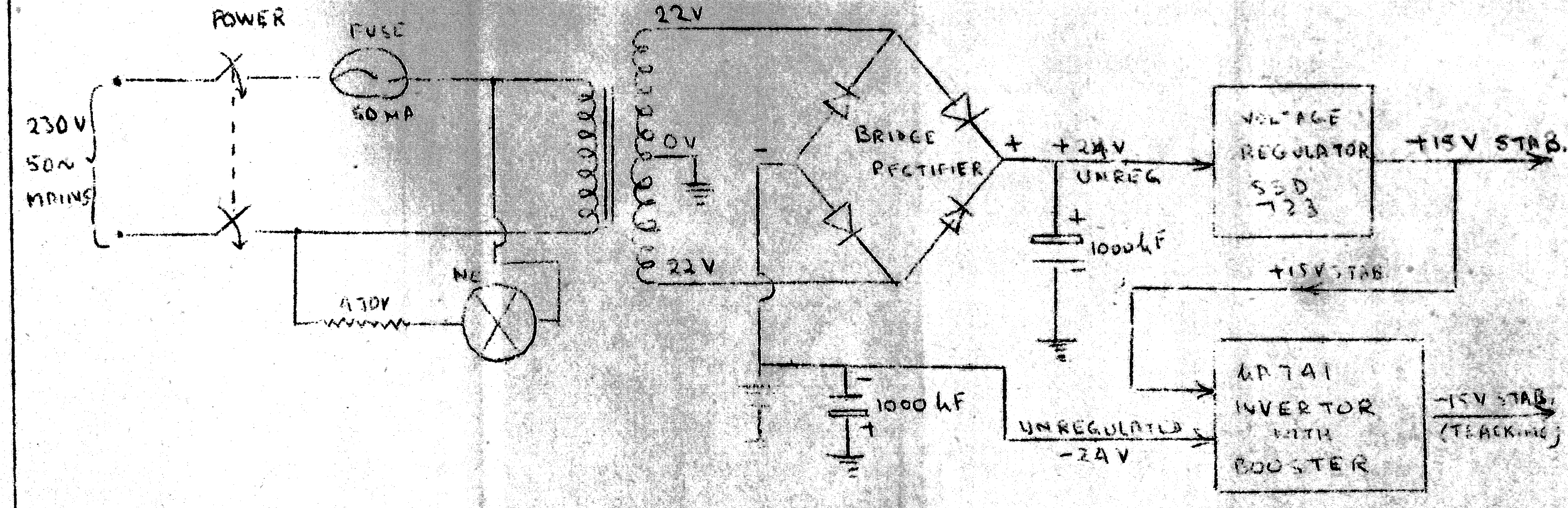


FIG. 5.11. LAYOUT OF POWER SUPPLY (SCHEMATIC)

(b) **READY:** It is an amber LED, which when ON, indicates that the system is in READY state for engagement practice.

(c) **FIRED:** It is a red LED indicating that the missile has been fired and the engagement time is not yet over. It is switched off either by the auto-reset pulse at the end of engagement or by an over-riding RESET operation.

(d) **GATHERING:** It is a green LED which is switched on during the engagement period as and when the missile is gathered on to the target.

(e) **HIT:**
(f) **MISS:** One of these two indications is switched ON at the end of engagement time to indicate the ultimate result. The indication is switched off by RESET operation, which also switches ON the READY indication simultaneously.

6.1.2 Front Panel Controls:

The controls located on the front panel (Refer Fig. 6.3) can be classified as System controls, Initial conditions controls and Dynamic controls.

(a) System Controls

These consist of:-

(i) POWER ON/OFF: It switches ON/OFF the 220v 50 Hz mains supply to the power supply

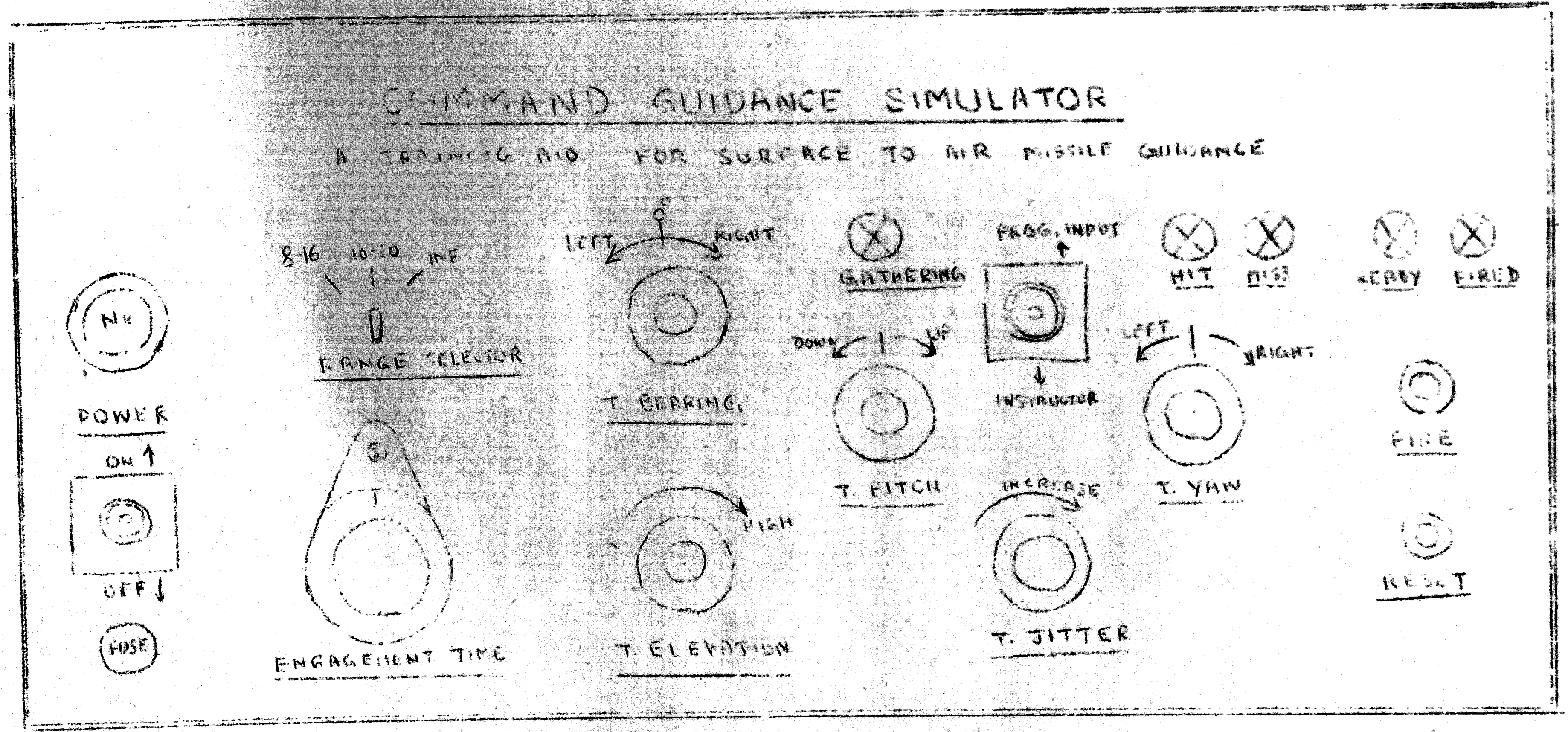


FIG 6.3 SCHEMATIC LAYOUT FRONT-PANEL — COMMAND GUIDANCE SIMULATOR

unit through a 50 mA fuse.

(ii) FIRE: It is a press-button SPDT switch, and simulates the Firing-Trigger for the launching of a missile.

(iii) RESET: It is also a press-button SPDT switch, which has to be pressed at the end of engagement to put the system back to the 'READY' state. It also provides an over-riding control to reset the system anytime during the 'FIRED' state of the system.

(b) Initial Conditions Controls

These are used for pre-setting the initial target conditions before a practice engagement, and consist of:-

(i) RANGE SELECTOR Switch: It is a 3 position band-switch corresponding to three ranges 6-16 sec., 10-20 sec. and INFINITE for setting up the Engagement time, (and hence simulating the target speed and its initial range). The third position is envisaged to be used primarily for maintenance work, so as to have the AUTO-RESET disabled, if required.

(ii) ENGAGEMENT TIME CONTROL: It is a linear potentiometer on which the Engagement time can be preset in two continuously variable decade ranges depending on the position of the RANGE SELECTOR Switch.

(iii) TARGET BEARING: The initial target

(iv) TARGET ELEVATION: bearing/elevation are preset with these potentiometers.

(c) Dynamic Controls

These controls determine the target trajectory during the engagement period, and consist of:-

(i) TARGET TRAJECTORY MODE SWITCH: It is a toggle switch which selects the target trajectory from either the programmed tape input (PROG.TAPE) or the Instructor's controls (INSTR.)

(ii) TARGET PITCH: These are the potentiometers

(iii) TARGET YAW: used for simulating the target movement in the viewing plane by the Instructor, when the system is selected in that mode.

(iv) TARGET JITTER: This potentiometer controls the amplitude of oscillations of the target, about a mean position to simulate a manoeuvering target.

6.1.3 Back Panel Terminals/Sockets:

Referring to Fig. 6.4, the following terminals and sockets are located on the back-panel of the

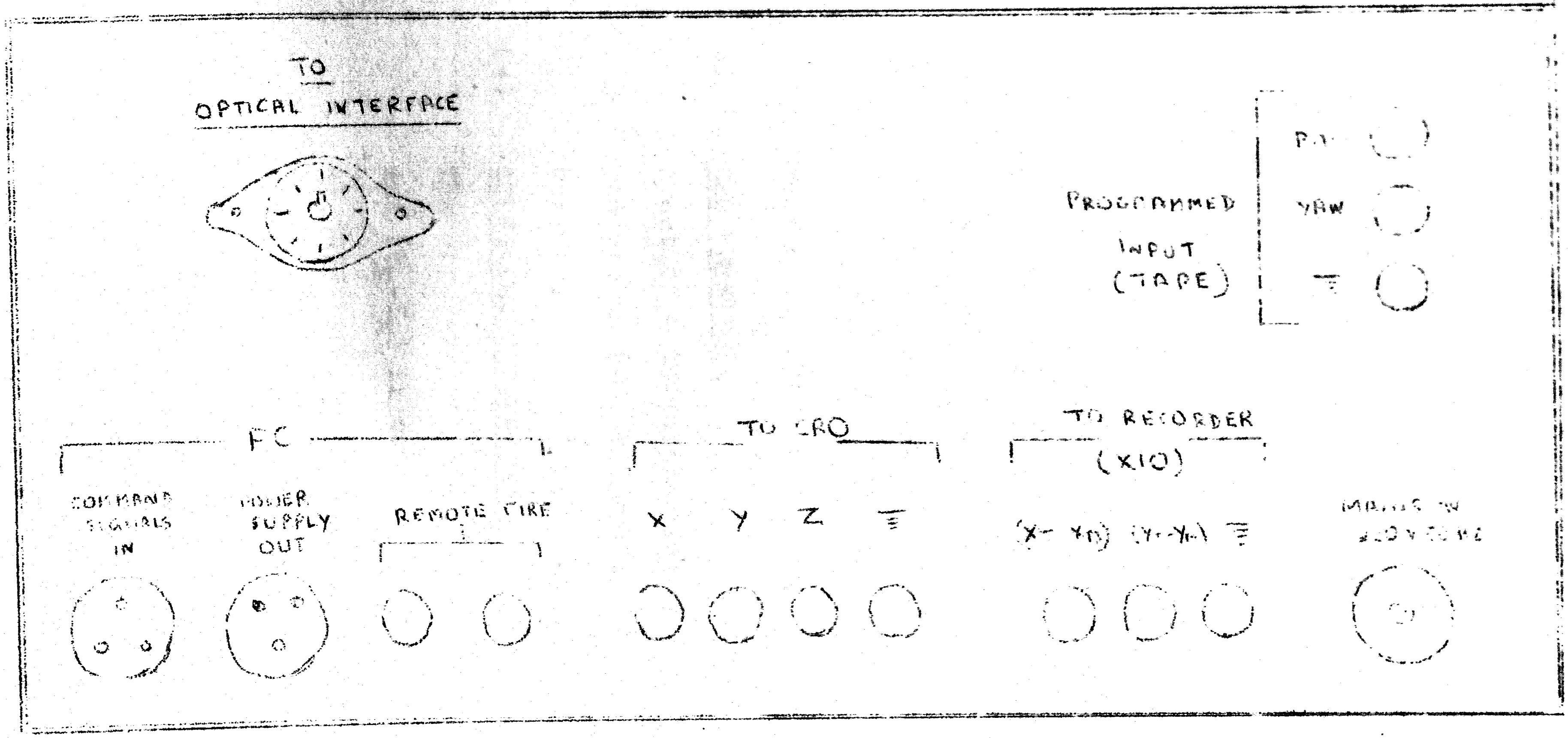


FIG. 6.4 SCHEMATIC LAYOUT OF BACK-PANEL — — COMMAND GUIDANCE SIMULATOR

Command Guidance Simulator:-

(a) FC P.S.SOCKET

It is a 3-pin socket for taking out $\pm$ 15 v and power supply ground to the FC unit.

(b) FC SIGNAL SOCKET

It is also a 3 pin socket for bringing in the pitch, the yaw and the signal ground from the FC to the simulator unit.

(c) REMOTE FIRE TERMINALS

The twin terminals are provided (in parallel to the FIRE button) for connecting a similar FIRE switch accessible to the trainee.

(d) CRO TERMINALS

A set of 4 terminals marked X_{CRO}, Y_{CRO}, Z_{CRO} and ground (E) are provided for connections to the CRO.

(e) STRIP-CHART TERMINALS

The error-voltages during guidance i.e. (X_T-X_M) and (Y_T-Y_M) in two planes are made available at these terminals for connection to a 2-channel strip-chart recorder, with a gain of 10. A separate ground terminal is also provided for the same.

(f) PROGRAMMED TAPE INPUT

These three terminals are provided for connection to programmed tapes for the dynamic control of the missile trajectory.

(g) OPTICAL INTERFACE SOCKET

The target and the missile co-ordinates i.e. X_T, Y_T, Z_T and X_M, Y_M and Z_M along with ground are brought out to an octal base to provide facility for connection to an optical interface for the Optical Projection type of display, (refer Chapter IV).

6.2 SETTING-UP PROCEDURE

The following procedure is recommended for setting-up the equipment:-

(a) Arrange the two units on a suitable table such that the trainee is seated about 30 cms. away from the scope. The simulator along with the Instructor can be on the side or behind the trainee.

(b) Connect FC to the simulator unit with two cables for the power supply and the pitch-yaw signals.

(c) Connect the appropriate CRO terminals on the simulator unit to the corresponding terminals on a CRO, set for x-y mode of operation. (Any single beam low-frequency CRO with facility for Z-modulation and 2v/cm gain on either channel can be used).

(d) Switch on CRO and with gain 2v/cm on either channel, adjust the position of the spot on the screen such that it is at the centre of the graticule.

(e) Connect a strip-chart recorder, if required.

(f) Connect REMOTE FIRE.

(g) Switch on the POWER on the simulator unit.

6.3 OPERATING PROCEDURE

It is envisaged that the normal battle-drill and words of command will be followed during practice engagements by the Instructor and the trainee. However, the following procedure for handling the simulator unit during such practices should be followed:

(a) Check that the system is in READY state, else press RESET.

(b) Preset the target bearing, elevation and the Engagement time.

(c) The simulated missile can be FIRED either by the Instructor or preferably by the Missile-Pilot himself from REMOTE FIRE on receiving appropriate communication.

(d) The target position can be dynamically controlled either by programmed tape-input or by the Instructor.

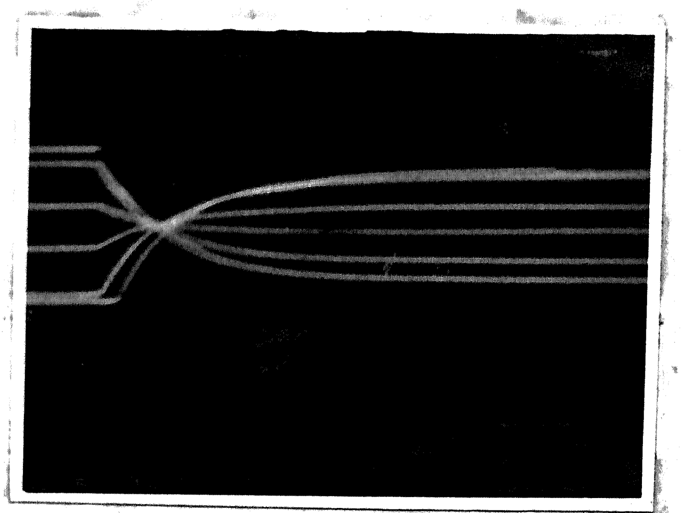
(e) The GATHERING indication will appear during the engagement period, and HIT/MISS indication shall be obtained at the end of engagement period (marked by the switching off of the FIRED indication).

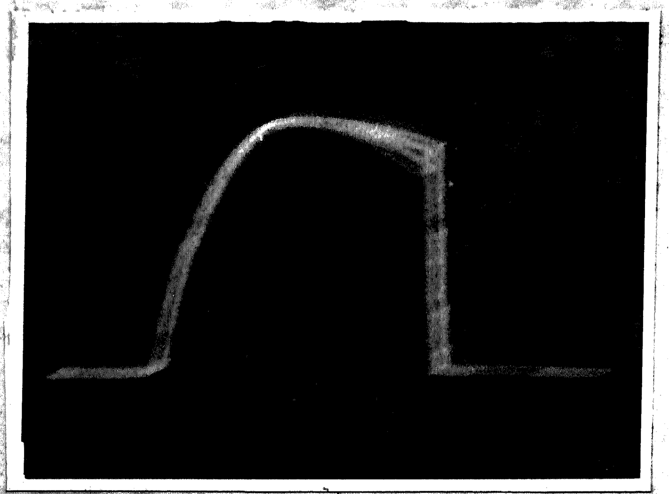
(f) Press RESET; and the system will go to the READY state instantaneously, and will be ready for another engagement practice.

6.4 TEST RESULTS

The simulator unit and the Flight-Controller have been tested for their functional performance, and have been found satisfactory over a period of about one month so far. Some photographs taken of a few typical waveforms are shown in Fig. 6.5.

The first photograph depicts a family of curves (X_M) corresponding to different settings of initial target bearing. It is to be noted that irrespective of target





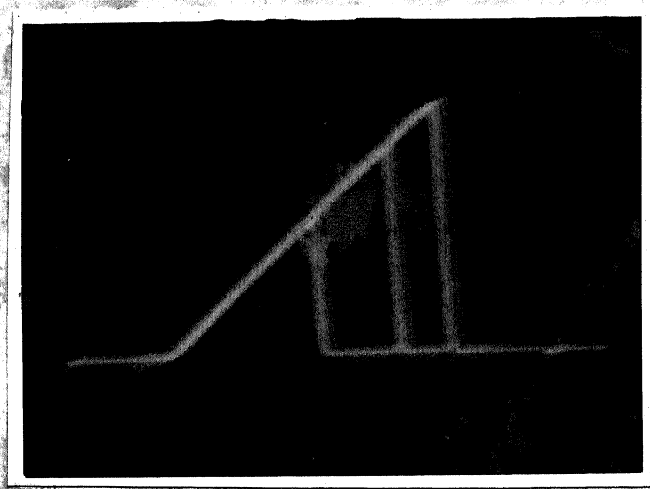


Fig. 6.5 Photographs- TEST RESULTS

bearing, the simulated missile reaches the cross-over point at the same instant of time. The second photograph shows the nature of Y_M obtained with different settings of initial target elevation. It is interesting to compare these practically achieved waveforms with the theoretically derived corresponding waveforms of Fig. 4.1. The last photograph shows the ramps (RAMP 2) produced for the analogue timing-clock with Engagement-time set at 10,16 and 20 secs.

6.5 CONCLUDING REMARKS

In this study, the basic simulation philosophy for the particular problem of simulated training of missile-pilots has been evolved and tested for its functional feasibility and credibility. Having developed the basic (L-mode) training version of the Command Guidance Simulator, the development of the proposed complete universal type of the simulator unit is a trivial job. However, the avenues for further research and development are:

(a) The interface units and the hardware for the proposed other two display systems i.e. the optical projection (for A-mode) and the special optical system to be used with live targets (in F-mode).

(b) Improvement in design and fabrication of the Flight-Controller unit to incorporate higher degree of reliability.

(c) Development of the programmed tapes for target trajectories.

A vital shortcoming of the present work done is that the user trials of the training-aid developed have not been carried out. The opinion of veteran Missile-Pilots, in regard to the effectiveness of the system developed, is also not known. It is hoped that the Defence R and D Organization shall take over this aspect along with the task of further development in the field.

BIBLIOGRAPHY

General References

1. Automation of Aircraft and Missiles by BLAKE-LOCK.

2. Flight Dynamics by KOLK.

3. Guided Missiles by MERILL.

4. Missile Aerodynamics by NIELSON.

5. Experimental Stress Analysis by JAMES W.DALLY and RILEY.

6. Analogue Computation by JACKSON.

7. Analogue Computation and Simulation by V.RAJARAMAN.

8. Operational Amplifier Design and Applications by BURR BROWN RESEARCH CORPORATION STAFF.

CHAPTER VI

OPERATING INSTRUCTIONS, TEST RESULTS AND CONCLUSION

This chapter deals with a brief overall description of the complete training-aid developed, with particular reference to its controls, setting-up procedure and operating instructions. The chapter concludes the study by summarizing the work done and indicating the scope for further development work.

6.1 GENERAL DESCRIPTION

The training-aid consists of a Flight-Controller, a Command Guidance Simulator unit and a single beam CRO. The three units are electrically connected through appropriate cables. Fig. 6.1 shows a photograph of a complete set up. Fig. 6.2 shows a close-up view of the FC (with top cover removed), and Figs. 6.3 and 6.4 show the front and the back panels of the Command Guidance Simulator unit. The indications, controls and terminals on the front and back panels are described below:

6.1.1 Front Panel Indications

The following indications are used:-

(a) POWER ON: It is a Neon lamp indicating that the mains power is ON in the system.

APPENDIX A

DERIVATION OF CORRECTION ANGLES FOR LAUNCH GEOMETRY

1. Correction Angle in Bearing-B_c

Referring to Fig. 3.2 and considering $\triangle$ PDL in the ground plane,

$$B_L = B_s + B_c \quad [\, B_L \text{ being the exterior angle}]$$

From $\triangle$ OLP in the launch-plane,

$$LP = R_o.\cos E_L$$

Then, from $\triangle$ DPL in the ground plane again,

$$\frac{\sin B_c}{DL} = \frac{\sin B_s}{LP}$$

$$\text{or } \sin B_c = \frac{DL \sin B_s}{R_o \cos E_L}$$

$$\text{or} \quad \sin B_c = \frac{d \sin B_s.\sec E_L}{R_o} \tag{A.1}$$

If E_s and therefore E_L is small, and since $d \ll R_o$, then $\sin B_c$ is small and $\simeq B_c$ (in radians)

Thus,

$$B_c \simeq \sin B_c = \frac{d \sin B_s.\sec E_L}{R_o} \tag{A.2}$$

2. Correction Angle in Elevation-E_c

Since B_c is small, the launch plane can be rotated about OP to coincide with the target plane without incurring any significant error as shown in Fig. A-1.

Then, $OL' = R_o$

and $OD \simeq R_o$

Also $E_s' \simeq E_s$ $\quad (h' << R_o)$

Then, from the diagram, it is clear that if the relative height 'h' was not assigned to the Director; then from $\triangle DOL'$, the correction angle is $\angle DOL'$. However, due to 'h', an additional component $\angle DOD'$ has to be incorporated.

$$\text{Thus, } E_c = \angle DOL' + \angle DOD'' \qquad (A.3)$$

The first correction angle is due to the displacement of the Director from the Launcher by distance 'd' and the other is caused by the relative height 'h' for gravity-drop compensation.

From $\triangle DL'L$, $DL' = d \cos B_s$

From $\triangle DOL'$,

$$\frac{\sin \angle DOL'}{DL'} = \frac{\sin E_s}{OL'}$$

$$\text{or} \quad \sin \angle DOL' = \frac{d \cos B_s . \sin E_s}{R_o}$$

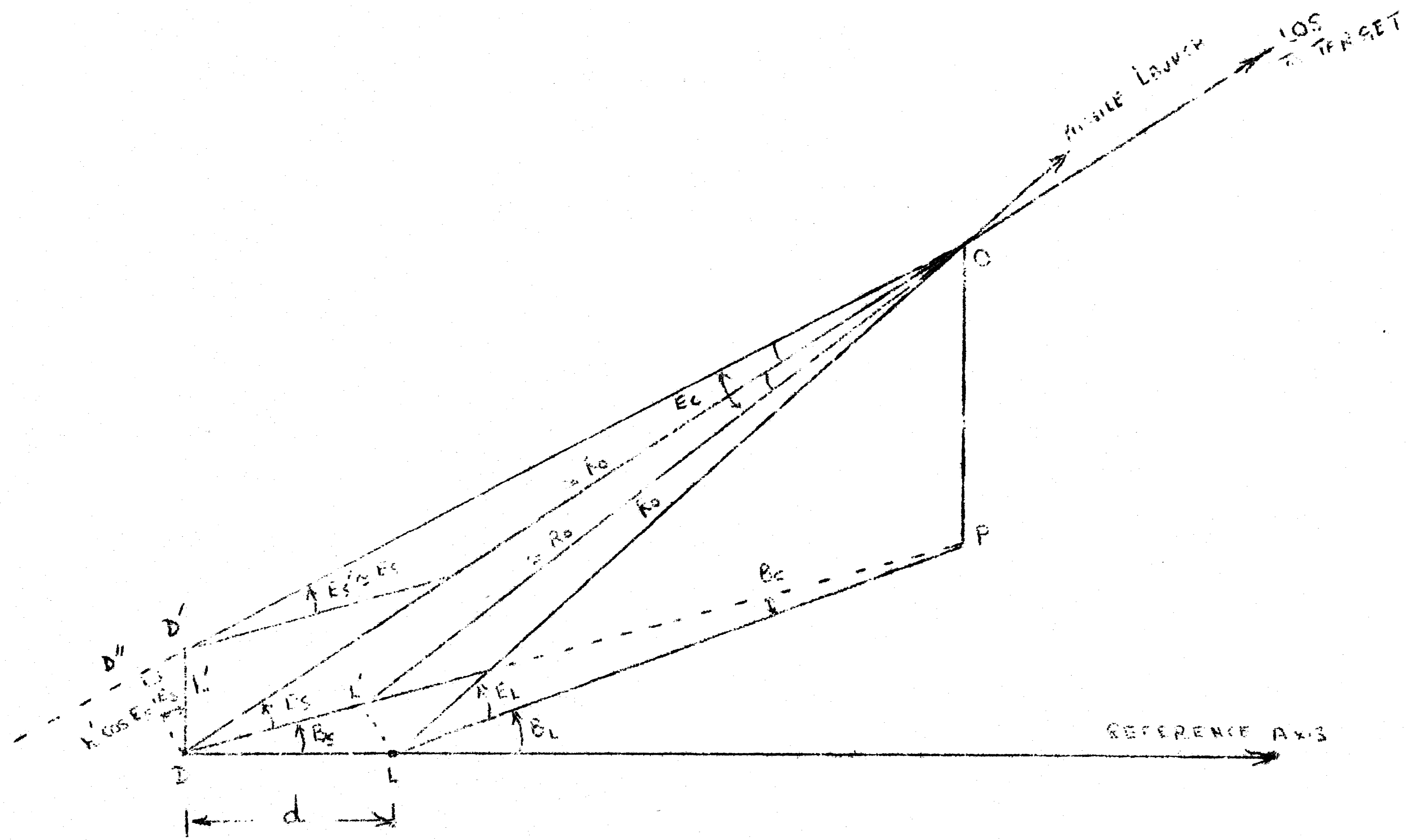


FIG A.1 GEOMETRICAL LAYOUT FOR COMPUTATION OF E_c

Since $\angle DOL'$ is small,

$$\angle DOL' \text{ (in radians)} = \frac{d \cos B_s . \sin E_s}{R_o} \quad (A.4)$$

Further, from $\triangle DD'D''$, $DD'' = h' \cos E_s$

and from $\triangle OD''D'$,

$$\sin \angle DOD'' = \frac{h' \cos E_s}{R_o}$$

$$\text{or } \angle DOD'' \text{(in radians)} = \frac{h' \cos E_s}{R_o} \quad (A.5)$$

Substituting (A.4) and (A.5) in (A.3),

$$E_c \simeq \frac{d \cos B_s . \sin E_s + h \cos E_s}{R_o} \quad (A.6)$$

APPENDIX B

ANALYSIS OF LINEAR VELOCITY COMPONENTS UNDER INITIAL LAUNCH CONDITIONS

Referring to Fig. 3.2, the missile is launched with a velocity V_M along LO. To determine the component velocities along x,y and z axes of the viewing plane; vector resolution as shown in Fig. B.1 is carried out.

It is obvious that

$$\overrightarrow{V_M} = \frac{V_M}{R_o} . \overrightarrow{LO}$$

From the geometry, the lengths of the intercepts of the various resolved components are:

$$LP = LO . \cos E_L$$

$$PO = LO . \sin E_L$$

$$LQ = LO . \cos E_L . \sin B_c$$

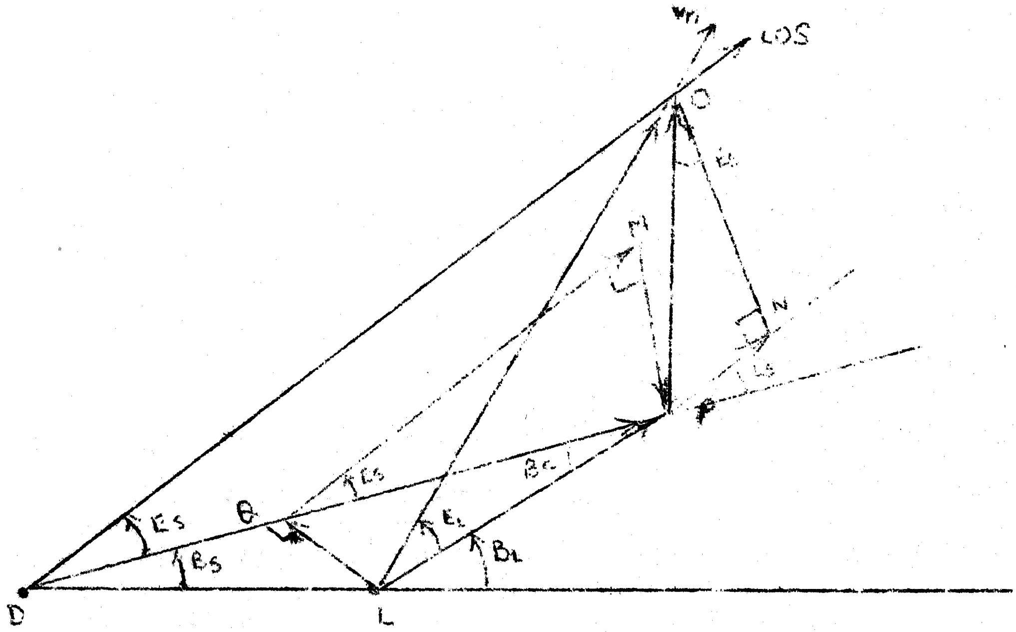
$$QP = LO . \cos E_L . \cos B_c$$

$$QM = LO . \cos E_L . \cos B_c . \cos E_s$$

$$MP = LO . \cos E_L . \cos B_c . \sin E_s$$

$$PN = LO . \sin E_L . \sin E_s$$

$$NO = LO . \sin E_L . \cos E_s$$



SUMMARY OF RESOLUTIONS :-

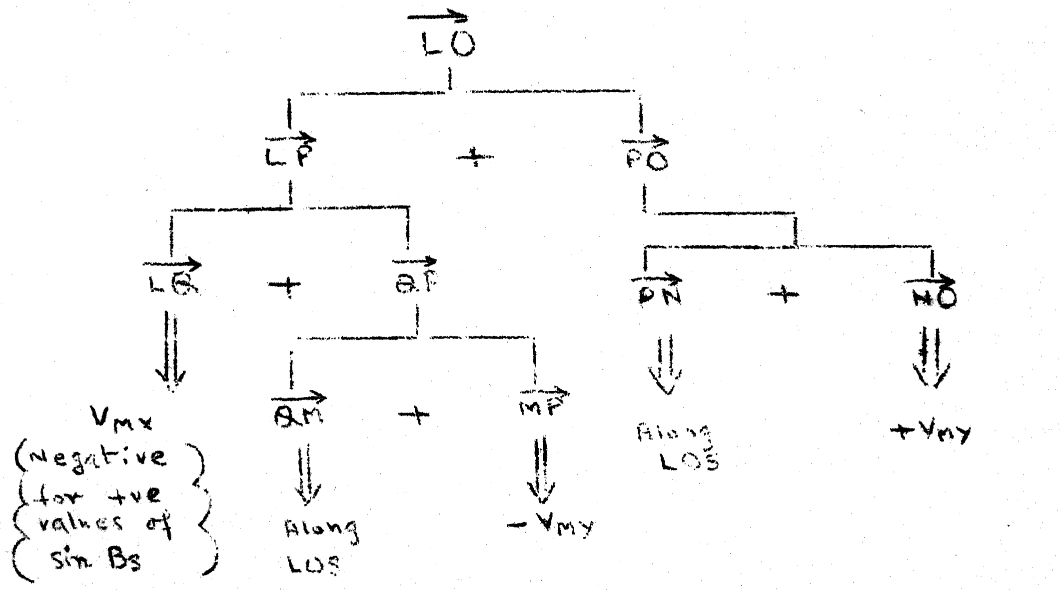


FIG. B.1 MISSILE VELOCITY VECTOR RESOLUTION DIAGRAM FOR INITIAL CONDITIONS

From the vector resolution diagram, it is noted that

(a) Components along PN and QM are acting along the LOS axis and contribute towards the motion of the missile along that axis normal to the viewing plane.

(b) Component along LQ acts along the horizontal axis of the viewing plane. It acts towards the left of the origin for target bearings (B_s) 0°–180°, and hence is a negative quantity, and towards the right for B_s values between 180°–360°, when it becomes positive.

(c) Components along NO acts always upwards, while the component along MP acts downwards along y-axis for positive values of E_s. (i.e. the target being above the Director-Launcher level on ground)

Thus, of V_x, V_y and V_z be the respective net components along the corresponding x,y and z axes of the viewing plane, then

$$V_z = \frac{PN + QM}{LO} . V_M$$

$$\text{or } V_z = V_M [\cos E_L . \cos E_s . \cos B_c + \sin E_L . \sin E_s] \tag{B.1}$$

$$V_x = - \frac{LQ}{LO} . V_M$$

or $V_x = - V_M \cdot \cos E_L \cdot \sin B_c$ (B.2)

and $V_y = \dfrac{NO - MP}{LO} \cdot V_M$

or $V_y = V_M \cdot [\sin E_L \cdot \cos E_s - \cos E_L \cdot \sin E_s \cdot \cos B_c]$ (B.3)

Approximations

Expressions (B.1) to (B.3) give the exact expressions, However, taking cognizance of the fact that B_c is small, and therefore $\cos B_c \simeq 1$.

The expressions then reduce to forms:-

$V_z \simeq V_M \cdot \cos (E_L - E_s)$

or $V_z \simeq V_M \cdot \cos E_c$ (B.4)

$V_x = - V_M \cdot \cos E_L \cdot \sin B_c$ (B.5)

and $V_y \cong V_M \cdot \sin (E_L - E_s)$

or $V_y \simeq V_M \cdot \sin E_c$ (B.6)

The expressions (B.4) to (B.6) are the same as derived by approximate analysis in section 3.3.1.1.

APPENDIX 'C'

SYSTEM PARAMETERS ASSUMED FOR HARDWARE REALIZATION

The following system parameters, based on an existing system, have been adopted for hardware realization:-

(a) Missile Characteristics

Coasting speed v_o	= 200 m/sec.(630ft/sec)
Delay between the instant fire and the instant of launch	= 2.0 sec.
Time taken t_o by missile to each cross-over point	= 2.0 sec.
Distance R_o covered in time t_o	= 1000 ft.(approx.)
Sustainer burn-out time	= 16 sec.
Maximum Engagement time	= 20 sec.

(b) Ground-Equipment

Distance between the Director and the Launcher-d	= 75 ft.
Correction h' for Gravity drop	= 87 ft.

(c) Guidance Link

Maximum FC outputs in both pitch and yaw plane	= $\pm$ 10v DC
Maximum control-surface deflection corresponding to input command	= $\pm 8^o$

For TF for Missile-servos (refer eqn. 3.31),

$$H_{so} = 1, \ K_5 = 0.015, \ K_6 = 0.02$$

For TF for the combined aerodynamics and SRD (refer equation 3.34)

$$H_{ao} = 1236.0, \ K_3=0.003, K_4=0.00109, K_7=0.092, K_8=0.0028$$

Scaling for Integrator (TF Block)

From the defined system parameters, 10v output of FC $\equiv 8^{o}$ of control-surface rotation (δ).

Since the angular velocity of the missile due to guidance command is $a/2u$ (section 3.8) and $a/\delta = 1236$ under DC conditions, the corresponding angular velocity w can be deduced as 1v output of FC $\equiv 0.8^{o}$ of δ

$$\equiv \frac{0.8^{o} \times 1236}{1260} = 0.656^{o}/\text{sec}.$$

The above relationship establishes the charging rate of the Integrator used in the TF block.